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Characterizing phosphorus dynamics in tile-drained agricultural fields of eastern Wisconsin

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SUMMARY

Artificial subsurface drainage provides an avenue for the rapid transfer of phosphorus (P) from agricultural fields to surface waters. This is of particular interest in eastern Wisconsin, where there is a concentrated population of dairy farms and high clay content soils prone to macropore development. Through collaboration with private landowners, surface and tile drainage was measured and analyzed for dissolved reactive P (DRP) and total P (TP) losses at four field sites in eastern Wisconsin between 2005 and 2009. These sites, which received frequent manure applications, represent a range of crop management practices which include: two chisel plowed corn fields (CP1, CP2), a no-till corn–soybean field (NT), and a grazed pasture (GP). Subsurface drainage was the dominant pathway of water loss at each site accounting for 66–96% of total water discharge. Average annual flow-weighted (FW) TP concentrations were 0.88, 0.57, 0.21, and 1.32 mg L^{-1} for sites CP1, CP2, NT, and GP, respectively. Low TP concentrations at the NT site were due to tile drain interception of groundwater flow where large volumes of tile drainage water diluted the FW-TP concentrations. Subsurface pathways contributed between 17% and 41% of the TP loss across sites. On a drainage event basis, total drainage explained between 36% and 72% of the event DRP loads across CP1, CP2, and GP; there was no relationship between event drainflow and event DRP load at the NT site. Manure applications did not consistently increase P concentrations in drainflow, but annual FW-P concentrations were greater in years receiving manure applications compared to years without manure application. Based on these field measures, P losses from tile drainage must be integrated into field level P budgets and P loss calculations on heavily manured soils, while also acknowledging the unique drainage patterns observed in eastern Wisconsin.

1. Introduction

Eutrophication, the accelerated nutrient enrichment of surface waters, impairs freshwater ecosystems in Wisconsin and around the world by causing unfavorable odors, algal blooms, and fish kills. Agricultural phosphorus (P) loss is the dominant driver of accelerated eutrophication in many freshwater lakes and streams (Carpenter et al., 1998a, b; Sharpley et al., 1994). A given field's susceptibility to P loss is influenced by soil properties, landscape position, management history, and current practices. There is also a disproportionality of P loss within a watershed; it has been estimated that 80% of losses come from 20% of the watershed (Sharpley et al., 2009).

Phosphorus leaching losses have been historically discounted because orthophosphate, the biologically active form of P, rapidly adsorbs onto soil surfaces. Furthermore, recent studies have concluded that tile drains are not main contributors to watershed P fluxes (e.g. Domagalski and Johnson, 2011; Sprague and Gronberg, 2012), although results from Gentry et al. (2007) indicate that tile drainage is a major contributor in specific watersheds. It is likely that P contribution from tiles can vary on a watershed-by-watershed basis and Ulén et al. (2011) make the case for the need for tile drains to be considered in P risk assessment. Other research highlights the risk of P loss from tile drains. Algoazany et al. (2007) determined that at four out of five continuously monitored sites in Illinois, tile drains exported more P than surface

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pathways due to large tile drainage volumes. There have also been numerous studies which suggest that preferential flow plays a role in leaching of P (e.g. Djodjic et al., 2000; Geohring et al., 2001; Hansen et al., 1999; Jensen et al., 2006; Kleinman et al., 2003, 2005; Simard et al., 2000), which would also play a key role in P export from tile drains. It is also clear that manure applications can lead to an increase in P loss from tile drains (Hernandez-Ramirez et al., 2011).

Beauchemin et al. (1998) concluded that P rich, flat, and clayey soils could contribute P to surface waters if tile drained. Eastern Wisconsin farmland fits these criteria. Soil tests conducted between 2005 and 2009 indicate that the average soil P levels in eastern Wisconsin counties are in the high to excessively high soil test category for most crops (University of Wisconsin Soil and Plant Analysis Laboratory (UW-SPAL), 2009). The lowest county average in Wisconsin is 33 mg kg^{-1}, which would be in the high soil test category for forage crops and excessively high soil test category for grain crops (Laboski et al., 2006). Additionally, considerable portions of eastern Wisconsin's cultivated acreage are tile-drained and receive annual applications of animal manure. However, P losses from tile drains in this landscape have not been quantified. Current conservation efforts in this region are focused on reducing surface P losses (e.g. Wisconsin Phosphorus Index); a greater understanding of tile P losses can aid in improving future conservation efforts.

The overall goal of this study was to quantify P losses from surface and tile drain pathways in this unique region, and identify key factors of the P losses. Collaboration among private landowners, the United States Geological Survey (USGS), and the UW-Discovery Farms program was used to identify field locations for intensive surface and tile monitoring. Specific objectives include: (i) determination of total and dissolved P loads and flow-weighted (FW) concentrations from surface and tile drains at an annual, monthly, and event-based time scale; (ii) evaluate the relationship between surface P losses and tile P losses; and (iii) evaluate drivers for P loss in these landscapes.

2. Materials and methods

2.1. Study area

The study was conducted between 2005 and 2009 on four tile-drained, in-field basins at three farms in eastern Wisconsin (Table 1). All farms are working dairies that participated in the UW-Extension Discovery Farms (www.uwdiscoveryfarms.org) program during the monitoring period and include two chisel plowed (CP) sites (CP1 and CP2), one no-tillage (NT) site, and one grazed pasture (GP). The CP1 and CP2 sites were located near Kewaunee in Kewaunee County. The NT site was located near Oconomowoc in Waukesha County and the GP site was located near Cleveland in Manitowoc County. The CP1, CP2, and GP site are within the Lake Michigan Watershed, while the NT site is within the Mississippi River Basin. Slopes ranged from 1% to 3% at NT and 2% to 6% across the CP and GP study sites. These fields were also selected because the soil test P concentrations were in the excessively high soil test category (Laboski et al., 2006) and because of the known historic annual or biennial manure applications (Table 1). Soil and crop management characteristics are summarized in Table 1.

The drain tiles at CP1 and CP2 were installed underneath grassed waterways and included randomly-spaced lateral drains. Drain placement at the NT site includes both parallel and randomly-spaced drains connected to a main lateral drain. The GP site has a randomly-spaced drainage system connected to a main lateral drain. Drains were installed at the CP and GP sites prior to 1990; the NT drains were installed prior to 2000. The drain lines are 0.15 m diameter clay tile at CP1 and CP2, 0.15 m diameter plastic tile at NT, and 0.3 m diameter concrete tile at GP. All drains are installed to a depth of approximately 1 m. There were no surface inlets upstream at any of our monitoring sites. At CP1 a tile blow-out was observed in 2007, but it is uncertain when the blow-out originally occurred.

The USGS determined surface and subsurface basin boundaries using personal communication with the producers and verification of the surface basin boundaries for CP1, CP2, and GP (Table 1, Stuntebeck et al., 2011). The tile drainage in each of these basins is located in an upland area in which the drainage tile was established above the groundwater table. The subsurface basin was estimated to be equivalent to that of the respective surface basin and descriptive maps are published in Stuntebeck et al. (2011). However, at the NT site, the boundaries for surface and subsurface basins were not the same based on site observations as well as annual runoff amounts. For the subsurface basin at NT, a regional groundwater model (GFLOW; Haitjema 1995) was used estimate the potential groundwater contributing area, which was determined to be 16.2 ha. Caution should be used when interpreting rainfall to runoff ratios and P loads per unit area from this site due to the uncertainty in subsurface drainage size. However, the uniqueness of this site's drainage characteristics warrant inclusion in this study. The agricultural management described in this study was performed across 60% of the NT surface watershed and 40% of the NT subsurface watershed, respectively. The remainder of the NT basin included a wood-lot and adjacent fields that were planted in corn and soybeans in 2006 and 2007 and corn and alfalfa in 2008. Field and surface boundaries for the NT site are provided in Stutebeck et al. (2011).

Table 1
Site characteristics of fields in eastern Wisconsin where surface and tile monitoring occurred.

Site	Years monitored[a]	Area drained (ha)	Soil test phosphorus (ppm)	Cropping system	Tillage practices	Dominant soil
CP1	2005–08	8.30	89[b], 70[c]	Continuous corn silage	Chisel plowed	Fine-loamy, mixed, active, mesic Haplic Glossudalfs
CP2	2005–08	5.30	64[b], 47[c]	Continuous corn silage	Chisel plowed	Fine-loamy, mixed, active, mesic Haplic Glossudalfs
NT	2006–08	16.20 (tile) 2.50 (surface)	85[d]	Corn–soybean	No-tillage	Fine, mixed, active, mesic Typic Hapludalfs
GP	2007–09	6.20	75[b], 140[d]	Pasture	NA[e]	Fine-loamy, mixed, superactive, mesic Typic Argiaquolls

[a] Water year (for example, 2005: October 1, 2004–September 30, 2005).
[b] October 22, 2007 sample date.
[c] April 21, 2009 sample date.
[d] November 2006 sample date.
[e] The GP site was tilled in the spring of 2009 for reseeding.

2.2. Field management

Field management activities were performed by private landowners; dates and rates of manure and fertilizer applications have been gathered from producer records. Sites CP1 and CP2 were cropped in continuous corn (harvested as corn silage) during the monitoring period and chisel-tilled in the fall, with the exception that alfalfa was grown in 2004 at CP1. Starter fertilizer was applied in 2005–2008 at CP1 and 2005, 2007, and 2008 for CP2; in 2005 starter fertilizer applied 21 kg-P ha^{-1} and in 2006–2008 starter fertilizer applied 8 kg-P ha^{-1}. Prior to initiation of this study, both CP1 and CP2 had alfalfa and CP1 had liquid dairy manure application in 2003 and 2004 and CP2 had liquid dairy manure application in 2004. The NT site was cropped in a corn–soybean–corn rotation beginning with corn in 2006. Starter fertilizer was applied in 2006 and 2008 at a rate of 10 kg-P ha^{-1}. Manure applications are listed in Table 2.

The GP site is an overwintering pasture for dairy cows and includes portions of nine paddocks (14.2 ha). The drainage basin (6.2 ha) only included areas within six of these paddocks. Cattle grazed in individual paddocks or combined paddocks between December and March of each year, with animal densities ranging from 50 to 350 cows ha^{-1} per paddock. During the remaining parts of the year, the same cows are grazed across all 137.7 ha of grazed pasture, only occasionally returning to this overwintering area. Phosphorus loading through natural deposition on the pasture was calculated based on rates of 67 kg-dairy manure d^{-1} and 0.66 g P kg^{-1} (NPM, 2009). Deposition of P within the basin was 277 kg-P ha^{-1} (December 2006–March 2007), 333 kg-P ha^{-1} (December 2007–March 2008), and 379 kg-P ha^{-1} (December 2007–March 2008) and there were two manure applications (Table 2). In the fall of 2008, 40% of the GP catchment was sprayed with glyphosate and on 17 April 2009, the treated area was tilled and replanted with a mixture of peas, oats, and grass mix, and fertilized with 27 kg-P ha^{-1}.

2.3. Sample collection and analysis

Daily rainfall data were collected at each site with a H340SDI Tipping Bucket Rain Gage (Design Analysis Associates, Logan, UT). Monthly snowfall data were gathered from the nearest National Weather Service data stations: Kewaunee, WI, 8 km southeast of the rain gauge at CP1 and CP2; Oconomowoc, WI, 8 km south–southwest of the rain gauge at NT; Sheboygan, WI, 19 km south–southeast of the rain gauge at GP. All long-term precipitation values are 30 year normals determined between 1970 and 2000 (NOAA, 2006), which were 77.0 cm for Kewaunee (CP1, CP2), 86.1 cm for Oconomowoc (NT), and 77.5 cm for Sheboygan (GP).

Permanent monitoring stations were installed and operated by the USGS, in cooperation with the Discovery Farms program, to continuously quantify and sample edge-of-basin surface runoff and tile drain flow at each site. A complete description of field equipment and sampling procedures used in this study is reported in Stuntebeck et al. (2008). At the edge-of-field at all sites, fiberglass H-flumes were installed perpendicular to the direction of overland flow to measure surface runoff. To measure tile flow at CP1, CP2, and GP, extra-large 60° V trapezoidal flumes were installed in-line with the tile and accessed using 3 × 1.5 m culverts placed vertically to bisect the tile. At the NT site, a trapezoidal flume, along with a protective box, was installed at the tile outlet, several meters beyond the field edge. Surface runoff and tile drain flow were monitored with a non-submersible pressure transducers (Sutron Accubar 4500–0125, Sutron Corp., Sterling, VA), coupled with nitrogen bubbler systems, and programmed using a CR10 or CR10X datalogger (Campbell Scientific, Inc., Logan, UT), with measurements collected every 1 min during surface runoff events and every 5 min during drain flow events.

Automated refrigerated samplers (ISCO 3700R sampler, Teledyne ISCO Inc., Lincoln, NE) were used to collect discrete time-based 1-L samples during runoff events; similar to those methods described in the USGS Wisconsin Water Science Center quality-assurance plan (Richards et al., 2006). Automated sample collection occurred every 35 min until peak flow, and then occurred every 1 h. If necessary, sampling was further reduced to every 3 h intervals to not exceed the sample storage capacity of the ISCO. Periodic grab samples were used to characterize prolonged periods of low-flow in the tile. If no grab samples were collected during tile flow, concentrations were estimated by substituting concentrations from drainage events that were comparable in volume, peak flow rate, and season. Samples were retrieved within 24 h of ISCO collection and transported at 4 °C to the University of Wisconsin-Stevens Point Water and Environmental Analysis Laboratory (UWSP-WEAL) for analysis. A discharge-weighted sample was produced for each runoff or drainflow event or prolonged period of low flow by calculating the percentage of the total runoff event or low-flow period volume that each discrete sample represented, collecting appropriate aliquots from each discrete sample by using a churn splitter, and combining the aliquots into one composite sample. Each composite sample was analyzed for TP and DRP.

Table 2
Dairy manure applications at CP1, CP2, NT, and GP. The manure applications to GP do not include direct deposition by grazing animals.

Site	Manure source and application	Phosphorus rate (kg ha^{-1})	Date of application
CP1	Sand-bedded, surface applied	5	4 January 2005
	Sand-bedded, surface applied	5	19 January 2005
	Liquid manure, injected	21	6 September 2005
	Liquid manure, injected	34	9 October 2006
	Liquid manure, injected	38	27 September 2007
CP2	Sand-bedded, surface applied	7	5 May 2005
	Sand-bedded, surface applied	52	14 October 2005
	Sand-bedded, surface applied	29	7 November 2006
	Liquid manure, injected	11	10 November 2006
	Sand-bedded, surface applied	18	23 January 2007
	Liquid manure, injected	22	31 October 2007
	Sand-bedded, surface applied	8	5 November 2007
NT	Solid manure, surface applied	63	3 December 2005
	Solid manure, surface applied	81	2 April 2008
GP	Liquid manure, injected	20	21 August 2008
	Liquid manure, injected	12	18 June 2009

Samples for TP were digested using the persulfate digestion method (APHA, 2005). For DRP analysis, water from the composite samples was agitated prior to filtration through a 1-μm pre-filter and a 0.45-μm mixed-cellulose ester membrane. The TP (after digestion) and the DRP was measured using the ascorbic acid method as described by Murphy and Riley (1962).

Surface runoff and tile drain flow data were collected at sites CP1 and CP2 from 2005 to 2008 and only subsurface data was collected in 2009 (2009 data was only used for event based analysis). Surface runoff and tile drain flow data were collected at NT and GP during 2006–2008 and 2007–2009, respectively. Samples with estimated concentrations were only used for the calculation of monthly and annual load determinations, and not used in any statistical analysis. From March through September 2009, the tile at GP was plugged; but surface flow and concentrations were used for monthly and annual load calculations.

2.4. Calculations and statistics

All statistical analysis was performed using SAS (SAS Institute, Cary, NC). Surface and tile DRP and TP loads were determined by multiplying the composite sample DRP and TP concentration by the respective flow volume. Sample loads were aggregated into annual loads on a hydrologic year basis, (e.g. hydrology year 2005 is from 1 October 2004 to 30 September 2005). Annual P loads were divided by their respective flow volumes, to give annual flow-weighted (FW) concentrations. Regression analysis was used to evaluate the relationship between concurrent surface and tile FW concentrations and between event drainage and P fluxes. For our purposes, an event was defined as a composite sample with a peak tile discharge rate greater than 0.003 $m^3 s^{-1}$ at CP1, CP2, and GP or greater than 0.007 $m^3 s^{-1}$ at NT. The delineation with peak flow rate was used to ensure only composite samples that represent peak hydrograph flow were used. Events where P concentrations were estimated were not used in any event analysis. Regression analysis (Proc REG) was used to evaluate the relation between surface and subsurface FW concentrations for all of the tile events that concurred with surface runoff events. The relation between event tile drainflow and TP or DRP load was determined across all events regardless if accompanied by surface flow. Log-transformations of event drainage and event TP and DRP load were performed prior to regression analyses (Proc REG) to test the relation between these two variables. The linear regression model was converted into a simplified expression based on non log-transformed data:

$$L = aQ^b \quad (1)$$

where L = event TP or DRP load and Q = event drainage. The exponent b in Eq. (1) represents the slope in the linear relationship

Table 3
Annual precipitation, annual tile (T) flow, and annual surface (S) runoff. The 30 year normals are 77.0 cm for CP1 and CP2, 86.1 cm for NT, and 77.5 cm for GP.

Site	2005			2006			2007			2008			2009		
	Precip	T	S	Precip	T	S	Precip	T	S	Precip	T	S	Precip	T	S
	cm														
CP1	77.4	8.2	5.4	73.9	24.3	4.7	56.4	8.5	5.2	69.6	23.8	4.3			
CP2	77.4	3.9	10.0	73.9	27.2	11.1	56.4	6.8	6.3	69.6	27.8	7.0			
NT				82.1	25.8	4.3	119.0	68.9	5.3	97.2	73.7	15.6			
GP							65.9	14.8	6.6	85.4	14.8	14.7	60.4	2.0	7.5

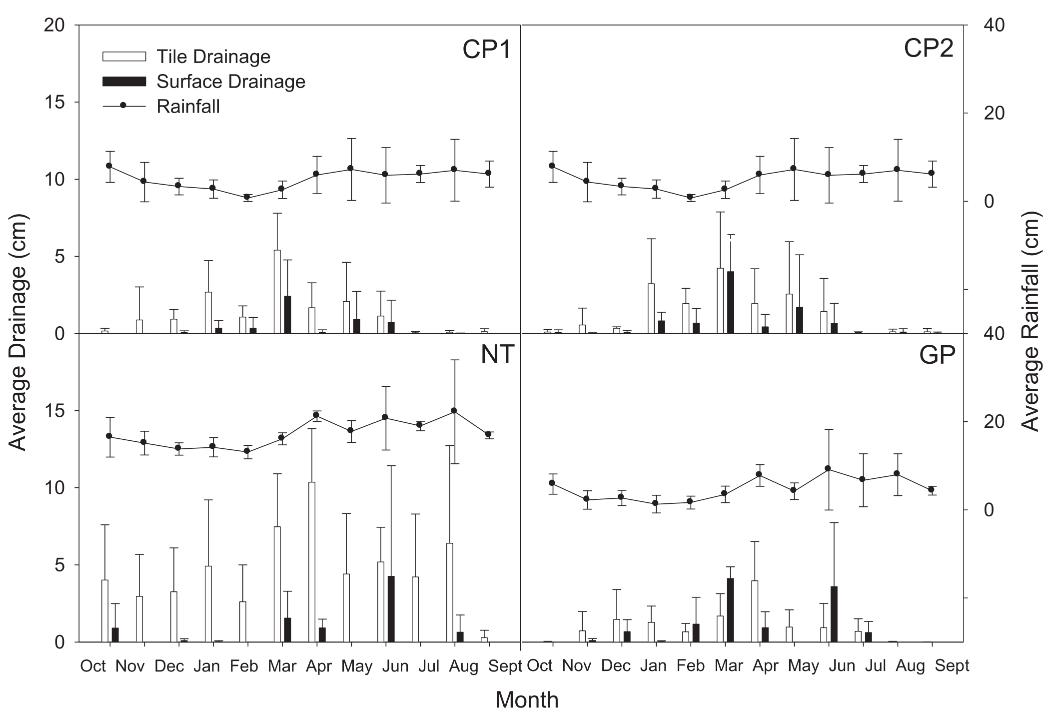

Fig. 1. Average monthly rainfall and drainage at sites CP1 (2005–2008), CP2 (2005–2008), NT (2006–2008), and GP (2007–2009) (error bars represent one standard deviation).

between the log-transformed values of event drainage and TP or DRP load.

3. Results

3.1. Precipitation and drainage

Annual precipitation at CP1 and CP2 ranged between 56.4 and 77.4 cm, which was at or less than the 30-yr normal rainfall (Table 3), which greater than normal rainfall occurred at NT in 2007, and less than normal rainfall occurred at GP in 2007 and 2008. Across all sites, tile drainage was greatest from March through May (Fig. 1), accounting for approximately half of the total annual tile drainage (58%, 55%, 40% and 47% for CP1, CP2, NT and GP, respectively), but all sites had tile flow occurring throughout the year. Tiles typically experienced periods of inactivity with respect to flow in the late fall to early winter months. The length and frequency of tile dormancy, however, varied across sites. The NT tile was dormant for 49 days during the study period, all of which occurred in the winter of 2006. The tile drain at CP2 was the least active and had intermittent periods of dormancy in all months except April of each year. The percentage of annual precipitation removed through tile flow at NT, which ranged between 31% and 76%, was much greater than the other sites. Tile flow as a percentage of annual precipitation fluctuated between 11% and 34% at CP1, 5% and 40% at CP2, and 17% and 22% at GP.

3.2. Annual P loads and flow-weighted concentrations

Annual TP loads for combined surface and tile pathways ranged from 1.06 to 12.36 kg ha^{-1}, across sites and years, and annual combined DRP loads ranged from 0.46 to 9.92 kg ha^{-1} (Tables 4 and 5). The two largest annual combined TP and DRP loads were measured in 2008 at GP and NT. Across all sites, both surface and tile TP and DRP loads were characterized by high inter-annual variability (Tables 4 and 5). When calculated across all sites and years, tile drains contributed between 21% and 52% of TP field losses and between 21% and 68% of DRP losses.

Average annual surface FW-TP and FW-DRP concentrations ranged from 2.66 to 6.48 mg L^{-1} and 0.75 to 5.21 mg L^{-1} across sites, respectively; average annual tile FW-TP and FW-DRP concentrations ranged from 0.21 to 1.32 mg L^{-1} and 0.17 to 0.89 mg L^{-1}, respectively (Tables 6 and 7). The GP site had the highest annual surface FW-TP concentrations (Table 6). At all sites, surface concentrations were greater and demonstrated more inter-annual variability than tile FW-TP and FW-DRP concentrations (Tables 6 and 7). In tile drains, average annual FW-TP concentrations were 1.2–1.8 times greater than average annual FW-DP concentrations. The ratio of FW-DRP:FW-TP was lower at CP1 and CP2 compared to other sites indicating that a greater proportion of TP was held in the particulate fraction at the CP sites. The NT site consistently exhibited the lowest tile FW-TP concentrations as well as the greatest disparity between surface and tile FW-TP concentrations. The lowest surface and tile FW-TP and FW-DRP concentrations at the NT site were measured in 2007, the year that no manure was applied, but had 119 cm of rainfall (Tables 3, 6 and 7).

3.3. Event P-loss dynamics

A total of 54, 39, 35, and 23 tile events were defined at CP1, CP2, NT, and GP respectively and 23, 22, 20, and 13 of the tile events at CP1, CP2, NT, and GP had concurrent surface flow. The duration of the events ranged from 9 to 276 h at CP1 (median = 61 h), 16 to 148 h at CP2 (median = 54 h), 15 to 156 h at NT (median = 46 h), and 13 to 235 h at NT (median = 48 h). The relation between concurrent surface and tile event DRP concentrations was significant at the CP1, CP2, and NT sites (R^2 = 0.49, 0.41, and 0.76, respectively), with slopes of 0.41, 0.33, and 0.34. The relation between concurrent surface and tile event DRP concentrations was not significant at GP (α = 0.05). Across all sites, the slope was 0.30 with an R^2 of 0.73 (Fig. 2), indicating that when surface drainflow is concurrent with tile drainflow, the DRP concentration in the tile is slightly less than one-third than that in the surface flow. The relation between TP concentrations in tile and surface flow was less consistent than DRP concentration. At CP1 and GP there was not a significant relationship between TP concentrations in surface and tile flow. At CP2 and NT, there was a significant relationship between TP concentration in surface and tile flow with slopes of 0.13 and 0.33 and R^2 values of 0.60 and 0.79, respectively. Across all sites,

Table 4
Annual total phosphorus (TP) loads in tile flow and surface runoff.

Site	2005		2006		2007		2008		2009	
	Tile	Surface	Tile	Surface	Tile	Surface	Tile	Surface	Tile	Surface
	kg ha^{-1}									
CP1	1.43	1.67	1.47	2.51	0.46	0.60	1.41	2.24		
CP2	0.24	1.17	1.47	4.55	0.39	2.10	1.53	1.42		
NT			0.49	2.27	0.53	1.05	2.73	6.93		
GP					1.25	4.14	2.63	9.73	0.27[a]	4.33

[a] A plug in the tile line severely limited drainage from March through September 2009.

Table 5
Annual dissolved reactive phosphorus (DRP) loads in tile flow and surface runoff.

Site	2005		2006		2007		2008		2009	
	Tile	Surface	Tile	Surface	Tile	Surface	Tile	Surface	Tile	Surface
	kg ha^{-1}									
CP1	0.78	0.95	0.86	0.41	0.27	0.22	0.81	0.38		
CP2	0.16	0.76	0.63	0.34	0.21	0.87	0.85	0.40		
NT			0.36	2.05	0.48	0.52	2.10	5.86		
GP					0.93	3.32	2.08	7.84	0.13[a]	3.32

[a] A plug in the tile line severely limited drainage from March through September 2009.

Table 6
Annual flow-weighted total phosphorus (FW-TP) concentrations in tile flow and surface runoff.

Site	2005		2006		2007		2008		2009	
	Tile	Surface	Tile	Surface	Tile	Surface	Tile	Surface	Tile	Surface
	$mg\ L^{-1}$									
CP1	1.76	3.09	0.61	5.38	0.55	1.14	0.60	5.27		
CP2	0.61	1.17	0.54	4.10	0.58	3.35	0.55	2.03		
NT			0.19	5.28	0.08	2.00	0.37	4.45		
GP					0.84	6.32	1.78	6.64	1.34	5.83

Table 7
Annual flow-weighted dissolved reactive phosphorus (FW-DRP) concentrations in tile flow and surface runoff.

Site	2005		2006		2007		2008		2009	
	Tile	Surface	Tile	Surface	Tile	Surface	Tile	Surface	Tile	Surface
	$mg\ L^{-1}$									
CP1	0.95	1.76	0.36	0.88	0.32	0.42	0.34	0.88		
CP2	0.40	0.76	0.23	0.30	0.31	1.38	0.31	0.57		
NT			0.14	4.77	0.07	0.97	0.29	3.76		
GP					0.63	5.07	1.41	5.35	0.63	4.47

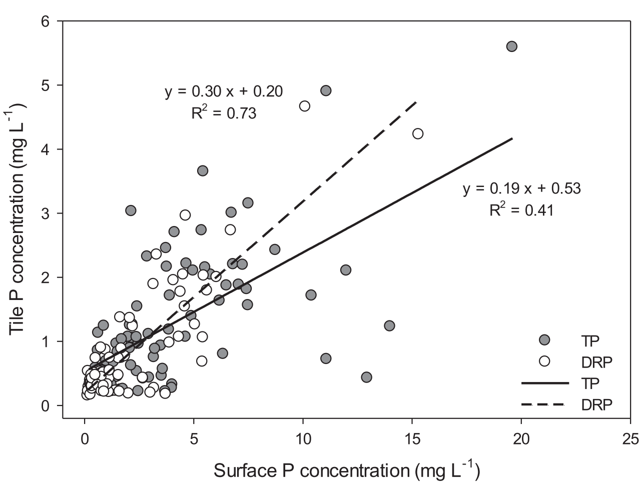

Fig. 2. Relation between event surface and tile total phosphorus (TP) concentrations and event surface and tile dissolved reactive phosphorus (DRP) concentrations ($n = 78$).

there was significant relationship between TP in surface and tile flow with a slope of 0.19 and an R^2 of 0.41 (Fig. 2).

On an event basis, tile drainage accounted for 55%, 48%, and 20% of the variability in TP load and 0.72%, 0.70%, and 0.36% of the variability in DRP loads from tile drains at CP1, CP2, and GP (Fig. 3). However, the slope (b) of the linear regression was only significantly different from 1 for TP loads at the CP1 site ($b = 0.80$, confidence interval = 0.64–0.96, $\alpha = 0.1$). This indicates that TP concentrations decreased slightly with an increase in drainage at CP1, while DP concentrations were not affected. At CP2, and GP drainage did not affect P concentrations. There was not a significant relationship between drainage and TP load or DRP load at the NT site (Fig. 3), suggesting that drainage had little effect on P concentration at this site.

Elevated P concentrations in tile drainage, compared to surface drainage, were often, but not consistently, observed at the CP1 and CP2. Tile TP and DP concentrations were at least 10% greater than surface concentrations in seven and 14 events, respectively; six and 13 of which occurred between January and May. Events when tile TP or DRP concentrations exceeded surface TP or DRP concentrations were predominately snowmelt events in which melting snow may have diluted surface runoff DRP concentrations.

An increase in tile P concentrations in events following manure application was not consistently observed. For example, CP1 and CP2 received five and seven manure applications each over the 4-yr study period, but concentration patterns only indicate an occasional increase in P concentrations following application (Figs. 4 and 5). An increase in TP or DRP concentrations occurred at CP1 after the 4 January and 19 January applications in 2005 (Fig. 4). Pre-application concentrations were 0.86 $mg\ L^{-1}$ of TP and 0.73 $mg\ L^{-1}$ of DRP, and increased to 2.32 $mg\ L^{-1}$ of TP and 1.37 $mg\ L^{-1}$ of DRP on 5 February 2005. An observable increase was also seen at CP1 after the manure application on 27 September 2007, with an increase in TP and DRP concentration occurring in an event five days after application. The most severe incidental loss event occurred after the 2 April 2008 manure application at the NT site, where 6.5 cm of rain fell over a four day span after application. Surface TP concentrations during this period peaked at 11.2 $mg\ L^{-1}$; tile TP concentrations rose from 0.02 $mg\ L^{-1}$ to 5.59 $mg\ L^{-1}$. This trend was not observed following the manure application at NT in 2006. After all other manure applications, there was not an immediate increase in P concentrations in drainflow.

4. Discussion

4.1. Contribution of tile drainage to flow and P loads

Contributions by tile drainage to total basin drainage (77%, 66%, 87% and 52% for CP1, CP2, NT and GP, respectively) were similar or slightly less than those reported in previous studies. Algoazany et al. (2007) found that tile drainage contributed 83–90% of total basin drainage from four nearly level fields in Illinois and Eastman et al. (2010) reported that 73% and 86% of catchment drainage came from tile lines at Quebec field sites with slopes of 2.6% and 0.8%, respectively. Slopes among sites in our study (2–6%) are greater than the slopes of these earlier tile drainage studies, which is likely the cause of lower surface drainage here compared to previous studies. Dissimilarity in slope is indicative of broader landscape divergences. Tile systems throughout much of the Midwest draw down the perched groundwater table in low-sloping fields (Fausey et al., 1995). In contrast, tile drains in Wisconsin are often placed above the regional groundwater water table and are used to accelerate drainage during spring snowmelt and large precipitation events, rather than lowering a water table.

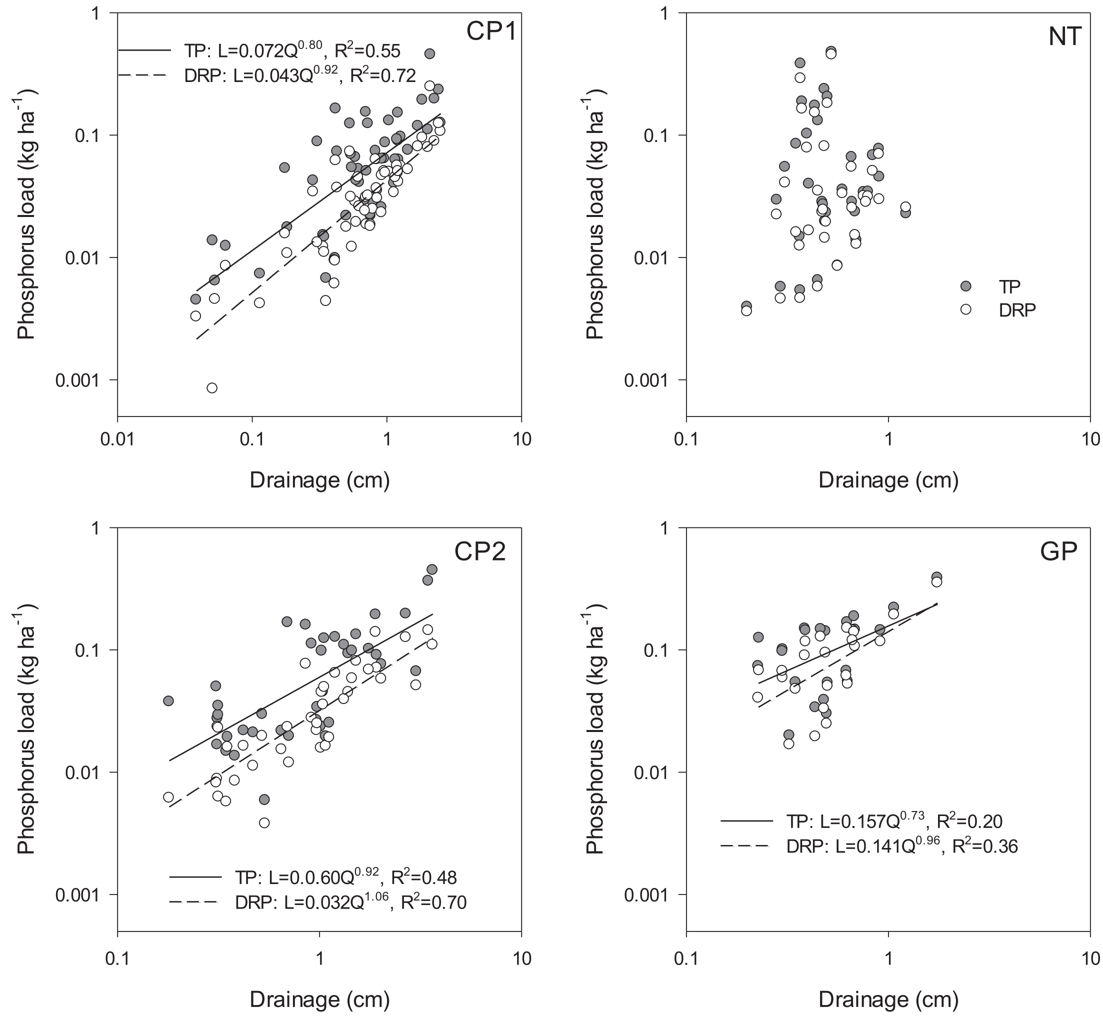

Fig. 3. Relationship between drainage and total phosphorus (TP) or dissolved reactive phosphorus loads on an event basis presented on a log–log scale (n = 54, 39, 35, and 23 for CP1, CP2, NT, and GP, respectively). Exponent (b) and coefficient (a) values are defined by Eq. (1) and R^2 values were determined by linear regression on log-transformed drainage and TP or DRP loads.

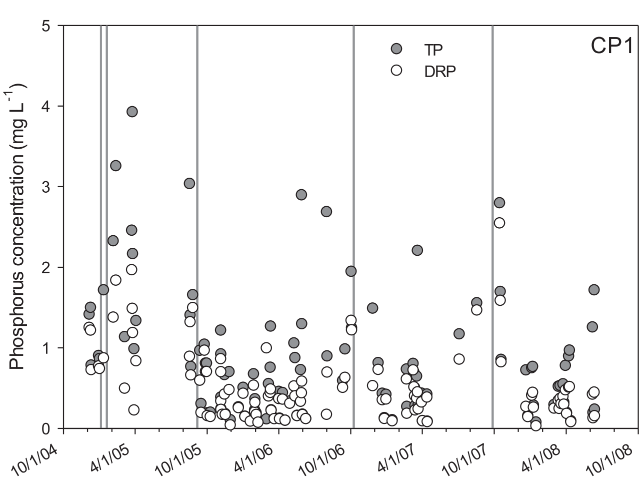

Fig. 4. Total phosphorus (TP) and dissolved reactive phosphorus (DRP) concentrations across the study period at CP1. The vertical gray bars represent timing of manure application. The data expressed here represents all collected concentration data regardless of peak flow rate and both flow-weighted sampling and grab sampling methods.

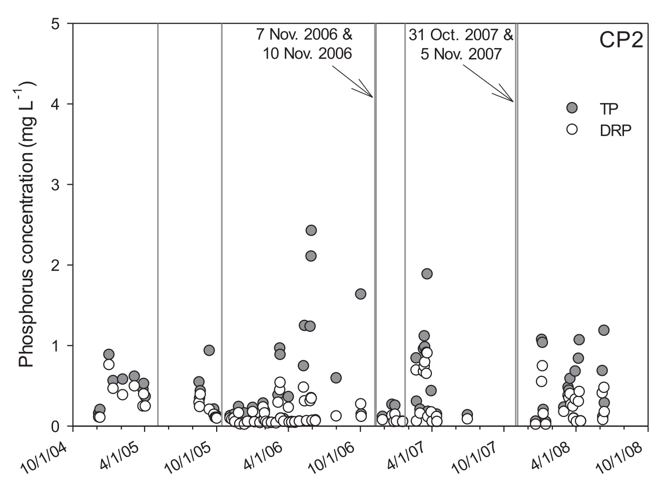

Fig. 5. Total phosphorus (TP) and dissolved reactive phosphorus (DRP) concentrations across the study period at CP2. The vertical gray bars represent timing of manure application. The data expressed here represents all collected concentration data regardless of peak flow rate and both flow-weighted sampling and grab sampling methods.

While the soil systems may be different between eastern WI and predominantly tile drained regions of the Midwest, the percent of annual precipitation exported through tile drainage at CP1, CP2, and GP (11–34%, 5–40%, and 17–22%, respectively) are similar to those reported in previous studies (Algoazany et al., 2007; Jaynes et al., 2001; Oquist et al., 2007). Algoazany et al. (2007) reported that 13–19% of annual precipitation was drained via tile lines over a seven-year study period in central Illinois. Jaynes et al. (2001) reported tile losses to be between 18 and 40% of total precipitation over four years in an Iowa field study. Oquist et al. (2007) found tiles drained 18–32% of precipitation under a conventionally managed field in southeastern MN. Further, these studies highlight that the inter-annual variability in tile drain efficiency in eastern Wisconsin is not uncommon. Across all sites, March and April had the greatest amount of tile drainage. This is similar to other reported seasonal drainage patterns in MN (Randall and Vetsch, 2005), IA (Schilling and Helmers, 2008), IN (Ruark et al., 2009), IL (Algoazany et al., 2007), and ON (Macrae et al., 2007).

Groundwater interception at the NT site generated tile drainage volumes much greater than those at the other sites. The subsurface basin at the NT site was difficult to define, and during wet periods, it is possible that the drainage area is much larger than our estimate. The continuously high flow rates indicate that tile drains were placed below the groundwater table. Caution should be used when interpreting drainage amounts, rainfall to runoff ratios, and P loads per unit area from this site; note that in 2008 the combined depth of surface runoff and tile drainage exceeded the annual precipitation to the basin. It remains unknown if this is a single site phenomenon or if this is commonly occurring scenario in this region.

The lower surface to tile drainage ratio at CP1 relative to CP2 may be partially due to a tile blow-out at the CP1 site. Blowouts, which occur when excessive pressure builds up in the tile drainpipe, open up direct pathways for surface water to enter the tile drain. At CP1, surface runoff would collect in a natural sub-basin and then drain through the blow-out; this unique drainage process delayed the onset and reduced the total volume of surface runoff. This phenomenon was first observed in 2007, but based on the lower surface to tile drainage ratios at CP1 compared to CP2 in 2005 and 2006, likely existed in previous years.

4.2. Phosphorus loading and concentrations

Annual tile P loads at these study sites, although lower than surface loads, were consistently greater than those reported in previous tile drainage studies (Tables 4 and 5). Eastman et al. (2010) reported average annual surface TP loads of 0.50 and 1.35 kg ha^{-1} from two fields with tile drainage that received inorganic P additions. In Illinois, measurements of average annual soluble P surface loads ranged from 0.05 to 0.13 kg ha^{-1} across six fields (Algoazany et al., 2007). Withers and Hodgkinson (2009) reported a comparable average annual tile FW-TP and FW-DP concentrations, 1123 and 257 $\mu g\ L^{-1}$, respectively, from a three-year field study in the United Kingdom. The tile drains in this UK study were installed at a depth of 0.8 m and overlain with gravel backfill to within 0.3 m of the surface which severely reduced natural filtration above the tile, increasing P transport to the tile and leading to elevated tile P concentrations and loads. Although for GP site, it should be noted that the measured P loss was only from the over-wintered portion of the landscape, which only represents 10% of the total area where cows are grazed. It would be erroneous to scale up these values across all pastured lands, as we do not have field measurements from less intensively grazed lands. However, these results highlight situations where P inputs can overwhelm the soils capacity to retain P.

Annual FW-TP and FW-DRP concentrations exceed the 0.1 mg L^{-1} concentration standard for eutrophication threshold for freshwater bodies, with concentrations at the GP having the consistently highest values. It is also interesting to note that the tile FW-TP concentrations at these sites, which ranged from 0.22 to 1.31 mg L^{-1}, were markedly greater than literature values from continuously monitored tile drainage studies in Quebec (0.08–0.30 mg L^{-1}), Denmark (0.02–0.11 mg L^{-1}), and Minnesota (0.04–0.05 mg L^{-1}) (Eastman et al., 2010; Grant et al., 1996; Hernandez-Ramirez et al., 2011; Oquist et al., 2007). Tile FW-DRP concentrations (0.17–0.89 mg L^{-1}) were higher than FW-Soluble P concentrations measured in Illinois (0.09–0.19 mg L^{-1}) (Algoazany et al., 2007) and in Indiana, where only 3% of the samples exceeded 0.1 mg L^{-1} (Hernandez-Ramirez et al., 2011). Excessively high soil test P levels in our fields likely contributed to the high P loads at these sites, relative to other studies. Measures of soil test P have repeatedly been found to correlate with concentrations of DRP in surface water (e.g. Andraski and Bundy, 2003), subsurface drainage (Chapman et al., 2003), and leaching studies (e.g. Maguire and Sims, 2002; Matula, 2009).

4.3. Phosphorus loss drivers

4.3.1. Drainage volume

Based on regression results shown in Figs. 2 and 3, event drainage controlled DRP loads to a greater extent than the TP loads. This suggests that sediment bound P exported from tile drains is more independent of flow, although mechanisms of transport of sediment from tile drains are not well understood. However, when compared to other nutrient fluxes, namely nitrate, the flow–flux relationships for TP and DRP have much lower coefficients of variation. For tile flow–nitrate flux relationships, other tile drain studies have reported coefficients of variation of 0.90 (Hernandez-Ramirez et al., 2011) to greater than 0.99 (Tomer et al., 2003). On an event basis, factors such as antecedent soil moisture, storm intensity, and time between manure application and storm events will affect tile P concentrations to a greater extent than nitrate concentrations (Culley and Bolton, 1983; Schelde et al., 2006).

This study has also shown that conditions exist where drainflow has no predictive value on P loss, such as when near-continual tile drainage caused by groundwater interception by tile drains occurred at the NT site, adding another layer of complexity to predicting P loss from these systems. At the NT site, the majority of the P loss occurred from the drainage events with the greatest flow rates. Events where flow rate exceeded 0.007 $m^3\ s^{-1}$ represented only 20% of the total drainage, but contributed 73% of the TP load and 70% of the DRP load. These findings are similar to those of Djodjic et al. (2000) who reported from work on seven tile-drained plots in Sweden that episodic losses, not total drainage, drove P loss. The most acute example of this phenomenon was in April 2008 when a drainage event at the NT site contributed less than 1% of the total drainage from the study period over 15% of the cumulative TP load. The results from this site are dissimilar to results from other sites in eastern WI, but similar to other studies that have demonstrated the potential for a few storm events to drive tile drain P loss (Macrae et al., 2007; Ulén, 1995; Djodjic et al., 2000; Withers and Hodgkinson, 2009; Zhao et al., 2001).

4.3.2. Manure applications

Manure application can partially explain inter-annual variability in P loads and concentrations from surface runoff and tile drainage, but this effect varied from site to site. Manure applications in 2006 and 2008 at the NT site resulted in much greater FW-TP and FW-DP concentrations surface and tile drainage for those years relative to 2007. What makes this of particular interest is that these seasonal patterns can be noted even though the NT site had groundwater contribution to tile flow and had manure applied only to 40% of the draining area. Surface FW-TP and FW-DRP concentrations and TP and DRP loads at CP2 were greatest in 2006, the year with the highest rate of manure application, and lowest in 2008, the year with the lowest rate of manure application. However, this trend was not present in tile drainage.

Event-based observations of P concentrations in drains also indicate that soil water flow pathways to tile drains are not consistently or immediately responsive to manure application, although two observable increases in tile P concentrations did occur at CP1. Tile drains had active drainflow during nine of the 14 manure applications at CP1 and CP2; the lack of observable increases after manure applications and increases in P concentrations long after manure application indicates that applying manure to soils when tile drains have active drainflow is not a primary cause of the increase in P concentration. Since event drainflow explained a large portion of the variability in TP and DRP loads, it is more likely that the main effect of the manure is by maintaining high soil test P concentrations, causing high concentrations of soluble P to exist along preferential flow pathways. This indicates that the cumulative effect of long-term manure applications is the primary cause of large P losses from this region. Although it is important to note that others have observed an increase in P concentration in tile drainage weeks to months after manure application (Macrae et al., 2007; McDowell and Sharpley, 2001; Withers et al., 2003). The risk of immediate P loss following a single application of manure needs to be more fully understood in this region.

5. Conclusions

Total and dissolved P losses from tile drains in Eastern Wisconsin can be substantial, and often much greater than reported in other studies in the corn-belt of the United States. However, extrapolations from these monitored fields to all tile-drained fields in the region must acknowledge the large degree of variability among drainage systems in eastern Wisconsin. It is possible that the loading behavior of the irregular and randomly-spaced tile systems common in Wisconsin will be more difficult to predict than the parallel grid tile designs present in other artificially-drained regions of the United States. Tile export of P from the fields monitored in this study (i.e. high clay content, often manured) indicate that this pathway is a clear contributor to surface water P in this region, representing 17–41% of the P loss. Thus, tile drainage P losses in eastern Wisconsin should be considered in the overall quantification of field level P loss. Any P loss mitigation strategies that only focus on reducing surface losses will not address roughly one-third of the P losses from drained agricultural fields.

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