ARTICLE IN PRESS

JGLR-01022; No. of pages: 10; 4C:

Journal of Great Lakes Research xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Journal of Great Lakes Research

journal homepage: www.elsevier.com/locate/jglr

# Annual and seasonal phosphorus export in surface runoff and tile drainage from agricultural fields with cold temperate climates

Chris J. Van Esbroeck [a,1], Merrin L. Macrae [a,*], Richard I. Brunke [b], Kevin McKague [c]

[a] Department of Geography and Environmental Management, University of Waterloo, Waterloo, ON N2L 3G1, Canada
[b] Environmental Management Branch, Ontario Ministry of Agriculture, Food and Rural Affairs, London, ON N6E 1L3, Canada
[c] Environmental Management Branch, Ontario Ministry of Agriculture, Food and Rural Affairs, Woodstock, ON N4T 1W2, Canada

ARTICLE INFO

*Article history:*
Received 30 July 2015
Accepted 31 December 2015
Available online xxxx

Communicated by Joseph V. DePinto

*Keywords:*
Agriculture
Seasonality
Reduced tillage
Lake Erie
Eutrophication
Water quality

ABSTRACT

Phosphorus (P) export from agriculture fields is contributing to algal blooms within Lake Erie. Field data quantifying the magnitude, timing and pathways of P loss are required to develop and test solutions. This study quantifies annual and seasonal losses of dissolved (DRP) and total (TP) phosphorus in surface runoff and tile drainage from three reduced tillage fields (October 2011 to April 2013). The non-growing season (NGS, October to April) was a critical period, with 83 to 97% of annual combined [surface + tile] runoff; 84 to 100% of DRP loss; 67 to 98% of TP loss occurring in this time. Annual export (May 2012 to April 2013) ranged from 0.332 to 0.419 kg TP/ha/yr and 0.034 to 0.096 kg DRP/ha/yr. Tile drainage contributed the majority of annual water export from fields (78 to 90%) whereas surface runoff contributed little (10 to 22%). Tiles exported 0.169 to 0.255 kg TP/ha/yr (40 to 77% of total TP load) and 0.017 to 0.023 kg DRP/ha/yr (19 to 67% of total DRP load). Thus, surface runoff, which primarily occurred during winter thaws, exported disproportionately more P relative to its contribution to flow. Phosphorus losses in tile drain effluent monitored over an additional NGS (October 2011 to April 2012) were elevated at two sites following the fall application of P. This study provides an improved understanding of edge-of-field P losses in humid, cold temperate regions that experience significant winter periods, and provides estimates of P loads from fields in which P conservation strategies are employed.

## Introduction

Considerable effort has been undertaken to reduce phosphorus (P) loading to surface water bodies within North America (*e.g.* Great Lakes Commission, 2012; Schindler et al., 2012) and elsewhere globally (*e.g.* Ulén et al., 2012; Withers and Haygarth, 2007). Harmful algal blooms and eutrophication, caused by excessive P loads, are problematic, and have been identified as a priority research area in the lower Great Lakes region of North America, particularly for Lake Erie (Great Lakes Commission, 2012). Observed increases in algal blooms in the Great Lakes over the past two decades (Kane et al., 2014; Winter et al., 2011) have been attributed to a combination of climate drivers (Bosch et al., 2014; Michalak et al., 2013) and increased dissolved reactive phosphorus (DRP) loading from tributaries (Baker et al., 2014; Daloglu et al., 2012; Joosse and Baker, 2011). Agricultural fields have been recognized as important non-point sources of P to water bodies (*e.g.* Sharpley et al., 2015). Consequently, there is public pressure to reduce agricultural losses.

Surface runoff was historically thought to be the primary export pathway for P leaving farm fields because of its ability to erode and transport P-rich surface sediment, and subsurface P transport was assumed to be small or negligible due to sorption processes (McDowell et al., 2001; Sims et al., 1998). However, it is now accepted that tile drainage is also an important pathway for P export (Dils and Heathwaite, 1999; Fisher, 2015; Gaynor and Findlay, 1995; Goulet et al., 2006; King et al., 2015b; Sharpley and Syers, 1979), particularly in soils with preferential flow pathways and drainage networks (Kleinman et al., 2015; Simard et al., 2000).

Best management practices (BMPs) such as no-till have been promoted extensively to reduce soil erosion *via* surface runoff. However, no-till systems may be problematic for the loss of DRP both in surface runoff (Elliott, 2013; Hansen et al., 2000; Tiessen et al., 2010) and in tile drainage (King et al., 2015a, 2015b; Kleinman et al., 2015) due to increased connectivity between surface soils and tile drains caused by enhanced macropore development (Enright and Madramootoo, 2004; Simard et al., 2000; Sims et al., 1998, Stamm et al., 1998; van der Salm et al., 2012) and/or the stratification of P in surface soil (Sharpley, 2003), which can lead to greater rates of P desorption to water (Hartz and Johnstone, 2006; McDowell and Sharpley, 2001; Sharpley, 2003).

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[*] Corresponding author at: Department of Geography and Environmental Management, University of Waterloo, Waterloo, ON N2L 3G1, Canada

*E-mail addresses:* cvanesbr@uwaterloo.ca, cvanesbroeck@mvca.on.ca (C.J. Van Esbroeck), mmacrae@uwaterloo.ca (M.L. Macrae), richard.brunke@ontario.ca (R.I. Brunke), kevin.mckague@ontario.ca (K. McKague).

[1] Present Address: Maitland Valley Conservation Authority, 1093 Marietta Street, Box 127, Wroxeter, ON N0G 2X0.

http://dx.doi.org/10.1016/j.jglr.2015.12.014
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Please cite this article as: Van Esbroeck, C.J., et al., Annual and seasonal phosphorus export in surface runoff and tile drainage from agricultural fields with cold temperate climates, J. Great Lakes Res. (2016), http://dx.doi.org/10.1016/j.jglr.2015.12.014

In fact, increases in the loading of DRP to the Western end of Lake Erie have been attributed to the increased use of conservation tillage strategies (Bosch et al., 2014; Kleinman et al., 2011; Michalak et al., 2013) as well as the surface broadcasting of fertilizers and autumn spreading combined with tile drainage (Kleinman et al., 2015; Sharpley et al., 2015).

Much of the existing knowledge of P mobilization in tile drains in North America, and/or the efficacy of BMPs, has focussed on warmer climates where frozen soils and snowmelt are not significant issues, or, in less humid cold climates. In regions with cold temperate climates and humid conditions, such as Ontario, Canada, agricultural fields experience significant rainfall and snow cover (with periodic winter thaws). Thus, P loss throughout all seasons of the year must be understood. In Manitoba, Canada, where the annual flow regime is dominated by spring runoff on frozen soils, Tiessen et al. (2010) found that P losses in surface runoff were greater from no-till systems relative to conventionally tilled systems, and, that most P was lost in the form of DRP during the spring snowmelt period. Liu et al. (2014) subsequently showed that converting no-till systems to rotational tillage (aggressively tilled every other year) significantly reduced P export in surface runoff. Mamo et al. (2005) found that P desorption to soil, and consequently leaching losses, were lessened under cooler temperatures. An improved understanding of year-round P losses from fields, and the pathways through which the P moves, may provide insight for effective management strategies in the Great Lakes region.

The successful reduction of P export requires an understanding of if and how management practices may increase or decrease the likelihood of P movement, and, the pathways through which the P is transported. Phosphorus export may be most effectively addressed by focusing management efforts on critical source areas of P, which are areas where there is an elevated source of P connected to surface water *via* runoff pathways (Pionke et al., 2000). Many of the existing P Indices and models do not account for tile drains as a pathway for P, or, do so in a simple fashion (Reid et al., 2012; Kleinman et al., 2015). Given the evidence regarding the contributions of tile drainage to P transport, an improved understanding of the individual and combined roles of surface runoff and tile drainage in P transport across all seasons of the year can be used to improve P indices and models as management tools. It is imperative that such estimates include the winter months, as they represent a critical period for annual hydrologic losses in the Great Lakes region (Macrae et al., 2007a, 2007b) and other regions that experience severe winter conditions (*e.g.* Enright and Madramootoo, 2004; Goulet et al., 2006; Kinley et al., 2007; Tiessen et al., 2010; Ulén et al., 2012).

Hydrologic losses, DRP and TP export were monitored in tile drainage and surface runoff from three reduced-tillage fields in Ontario over an 18-month period to (1) Characterize and quantify seasonal and annual edge-of-field losses of hydrologic losses and P in tile drainage and surface runoff; and (2) to demonstrate variability in non-growing season (NGS) losses of P in tile drain effluent over two NGS periods and relate this to P application. This knowledge will identify opportunities to manage P application and tillage practices to reduce overall P losses from fields in the Lake Erie watershed and in other regions with comparable climates.

## Methods

### Site descriptions

Research for this study was conducted at three sites across Ontario (*BVL*: UTM 18T 547,572 m E, 5,003,684 m N; *ILD*: UTM 17T 472,219 m E, 4,767,583 m N; *LON*: UTM 17T 466,689 m E, 4,832,203 m N) (Fig. 1). The sites have humid continental climates (Dfa/Dfb Koppen Classification) with warm, humid summers and cold, snowy winters. Long-term 30-year mean annual temperatures are similar at the BVL (7.0 °C) and LON (7.2 °C) sites but slightly warmer at the ILD site (8.2 °C) (Environment Canada, 2013). Mean daily temperatures generally fall below freezing from December through March in this region (Environment Canada, 2013). Long-term (30-year mean) annual precipitation received is slightly lower at the BVL (1004 mm, 16% as snow) and LON (1024 mm, 30% as snow) sites in comparison to ILD (1247 mm, 17% as snow) and is evenly distributed throughout the year.

Soil characteristics and slope varied among the sites (Table 1). Soil textures ranged from silt loam to clay loam (Table 1). Soil at the BVL site was Bainsville silt loam, which is poorly drained with a clay layer found at 1 m depth (Matthews et al., 1957). The area is flat relative to the other sites (Fig. 1). The ILD site has hummocky topography (Fig. 1), with imperfectly drained Thorndale Silt Loam and Embro Silt Loam soils (Hagerty and Kingston, 1992). The LON site is located on gently undulating terrain (Fig. 1), with imperfectly drained Perth Clay Loam soil (Hoffman et al., 1952). Soil test P (STP; Olsen-P) levels (measured in 2011) in the top 15 cm are similar across the sites (~12–15 mg/kg Olsen-P, Table 1) and rapidly decline below the surface at all sites to 5 to 8 mg/kg between 0.15 and 0.45 m, and 4 to 6 mg/kg between 0.45 and 0.75 m.

All sites are located on working farms, with reduced tillage systems and a corn-soy-winter wheat rotation. Specific tillage and fertilization methods, and specific crop rotations differ slightly between the sites (Table 1). At the ILD and LON sites, P is applied to maintain STP levels with regard to matching crop P removal rates (based on removal over a three year crop rotation), and, all three sites use a reduced tillage strategy (rotational, non-aggressive disturbance). At the BVL site, fields are typically subjected to a shallow ridge till (5 cm depth) in the autumn following winter wheat harvest, and a shallow (5 cm deep) disk harrow in spring (April) prior to corn. No tillage is done prior to or following soybeans. No mineral P is applied at the BVL site, although manure is applied periodically (prior to the study, dry poultry manure was last applied in autumn 2007 at 1 Mt/acre). At the ILD site, tillage is only done once per three-year rotation, in the fall following winter wheat harvest. At the ILD site, liquid poultry manure (50-25-32) was surface broadcast following the harvest of winter wheat and left (not incorporated) on the surface (Oct. 10, 2011), with a cover crop (Oilseed Radish) planted immediately. Approximately one month later (~Nov. 7, 2011), MAP was surface broadcast in strips (25 cm wide at surface, 10 cm wide at strip base, 15 cm beneath surface) and blended throughout the strip to a depth of ~15 cm. At the site, MAP is also applied in subsurface bands (at 3 cm depth with seed) at the time that winter wheat is planted (autumn 2010, prior to start of study). No P is applied for corn or soybeans at the site. At the LON site, P is surface broadcast (October 1, 2011) following winter wheat harvest (late July, 2011), and incorporated to a depth of ~6 cm using vertical tillage approximately 2 days after P is applied. Red Clover cover crops are seeded in spring (surface applied on top of winter wheat). For corn, mineral P is applied in bands in the subsurface with seed (~6 cm depth) (May 1, 2012). Fields are vertically tilled in both spring and autumn for years with corn crops, but no tillage is done and no P is added in years with soybean crops. Due to the Ontario climate, spring planted crops are seeded in April–June and harvest is typically completed by November. The sites were selected because they were similar in size and management approaches. Combined runoff (tile + surface) from the field was isolated to the field of interest (*i.e.* no adjacent contributing areas), and could be easily monitored because it drained *via* a common outlet on one side of the field rather than *via* numerous smaller pathways (Fig. 1). The BVL site is unique from the other two sites because it has two French drains in the field that permit surface water to enter the tile drainage system. The tile drainage system at the ILD site also receives discharge from two catch basins located in the farm driveway (these drain a very small section of the driveway only). Observations of discharge through these catch basins into tile drains during rainfall occurring on dry to moist soils (where it was apparent that the catch basin was the only source of water to the tile drain) demonstrated that these catch basins contribute very little flow to tiles, and we estimate that their contribution is <1% of overall flow

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