Effects of Hydroclimatic Drivers and Tillage Practices on Runoff Generation and Phosphorus Losses Through Drainage Tiles from Agricultural Fields with Sandy Loam Soils

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions accepted by my examiners. I understand that my thesis may be made electronically available to the public.

Abstract

Effluent from agricultural tile drains has been identified a source of phosphorus (P) to water bodies, contributing to algal blooms and water quality degradation. Reduced till (RT) or no-till are Best Management Practices (BMP) often used to limit the export of particulate P (PP) in runoff. However, existing research has shown that no-till may increase losses of dissolved reactive phosphorus (DRP) in tile drains. Much of the existing knowledge has been generated in clay soil, where preferential transport between the surface and tile drains prevails. Moreover, much of the previous work done has been done during the growing season. It is unclear if, and how P losses under RT tillage practices compare to those under annual tillage (AT) in the sandy loam soils of southern Ontario, and, how these BMPs perform year-round in climates where snowmelt accounts for significant amount of annual runoff. The objectives of this research are to quantify year-round losses of runoff, DRP and total phosphorus (TP) from tile drains beneath RT and AT plots and to demonstrate the role of seasonality on losses. This research also relates biogeochemical and hydrological responses in drainage tiles to precipitation inputs and antecedent soil moisture conditions as drivers of effluent and P-export. Tile runoff and chemistry were monitored for a 28-month period at two adjacent sites under similar management practices. Both runoff and P-export were episodic across all plots, with the majority of annual losses occurring during a few key events under heavy precipitation or snowmelt. Most losses occurred during the non-growing season between October and May. Tillage methods did not affect DRP or TP concentrations or loads in tile drain effluent. Tile discharge and responses were governed by soil

moisture conditions such that flow only occurred at soil moisture conditions that fell above a threshold value (above field capacity, near saturation). Runoff responses during the non-growing season were high because soils sit at or close to this threshold consistently. Strong relationships were found between volume of discharge and DRP and TP loads, indicating that with known baseline conditions, simple hydrometric data may be able to predict biogeochemical and hydrologic responses in drainage tiles under sandy loam soils.

This study emphasizes the importance of the non-growing season and snowmelt in annual P losses from tile drains, illustrating that BMPs must be effective during the winter months to reduce P losses. The cumulative BMPs used at the study site appear to be fairly effective at minimizing P losses in tile drain effluent under both RT and AT plots. This study also provides useful insight for modeling runoff and P losses in tile drainage.

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Chapter 1 – Introduction and Problem Statement

Eutrophication is an issue that affects many aquatic ecosystems globally. The over-enrichment of lakes and waterways with nutrients in runoff results in harmful algal blooms (HABs). This process causes water quality and toxicity issues, fish kills, changes to species composition, loss of biodiversity, and the formation of "dead zones" (Pierrou, 1976; Bennett et al., 2001). Lakes and other water bodies can lose ecological, aesthetic and economic value as a result of eutrophication. This type of environmental degradation is also detrimental to humans; affecting drinking water, industrial activities, fisheries and recreational economies (Pierrou, 1976; Sharpley et al., 1995; Bennett et al., 2001; Filippelli, 2002). Studies have shown that HABs in freshwater lakes are attributed to elevated P-concentrations from watersheds. Many North American lakes, including Lake Winnipeg in Manitoba, Canada (Schindler ET AL, 2012) and Lakes Erie and Simcoe in Ontario, Canada (Evans et al., 1996; Winter et al., 2007; LEEP, 2014) are experiencing these issues and consequently, there is significant public pressure to reduce P loads to these lakes. Some of the nutrients are derived from agricultural fields. Farmers are under pressure to use BMPs such as reduced tillage to reduce nutrient loads, but there is uncertainty in the efficacy of Best Management Practices (BMPs) across the landscape.

Chapter 2 – Literature Review & Thesis Objectives

2.1 Phosphorus cycling and P as an environmental issue

Phosphorus (P) is commonly the limiting nutrient for the vast majority of North American mesotrophic and north-temperate lakes (Howarth, 1988; Schindler 2006).

Phosphorus loading into these aquatic systems creates a nutrient imbalance where increased levels of P results in higher net primary production (Howarth, 1988; Sharpley et al., 1995; Correll, 1998).

Sources of P in receiving surface water bodies can be derived from point and non-point sources. Point sources are localized pollution sources such as mines, untreated sewage pipes, and industrial activities. Non-point sources such as agricultural and urban runoff are diffuse sources of P that are derived from many different origins that will have a cumulative effect on nutrient loading into surface waters, potentially resulting in eutrophication. The dispersed nature of non-point sources of pollution creates a scenario that is very difficult to measure or manage because of its diffuse nature and effective policies and initiatives to reduce the export of P into aquatic ecosystems and prevent eutrophication faces significant hurdles (Sharpley et al., 1995; Bennett et al., 2001; Mitsch et al., 2001). The ultimate goal of limiting and reversing anthropogenic impacts on the P cycle at a watershed scale is also extremely challenging. After conservation and prevention efforts have begun, it can take many decades for P-enriched soils to experience drawdown in exports due to the legacy P in the environment (Sharpley et al., 2014).

2.2 Agriculture and Phosphorus

Phosphorus is an essential nutrient commonly used on agricultural fields, along with nitrogen and potassium. However, the use of P in modern agricultural practices is not efficient and a large portion of applied fertilizers can be eroded as particulate-P or leached as dissolved-P. Thus, the aim of many best management practices (BMPs) is to prevent eutrophication by reducing the amount of agricultural-P that is exported (Smil, 2000; Bennett et al., 2001; Hansen et al., 2002; Cordell et al., 2009). Furthermore, unlike most natural ecosystems, nutrient cycling is not tightly closed in agricultural watersheds due to the fact that crops are removed from the system, manure and fertilizers are often added, and agricultural soils are also prone to erosion and nutrient runoff. As a result, the residence time of P is much lower in agricultural fields compared to undisturbed ecosystems (Eghball et al., 2002; Quinton et al., 2010).

Cultivation disturbs the natural stability of soil organic matter and organic-P, altering P immobilization-mineralization activities. These modifications can have particularly significant implications to soils that are nutrient poor and can have long term affects on plant production, decomposition and nutrient cycling (Stewart and Tiessen, 1987; Condron et al., 1990; Quinton et al., 2010). Larger inorganic pools of P are often accumulated over time in soils that receive regular fertilization (Condron et al., 1990; Williams and Haynes, 1992; Eghball et al., 2002) As a result, agricultural fields are more prone to P export in surface and subsurface runoff compared to soils in natural landscapes. The over application of P also has long-term implications, soil that has been historically over fertilized requires a lengthy period of time (up to many decades), before P-concentrations will drop below environmentally acceptable levels that do not export excess amounts of P (Van Bochove et al., 2012; Sharpley et al., 2014).

On agricultural landscapes, P can be directly exported to surface waterways via two primary pathways: surface/overland flow and subsurface flow. Overland flow occurs when effluent moves along the surface of the soil during large/high intensity rainfall or snowmelt events and can export large amounts of P from agricultural soils. The transport of P occurs primarily in surface waters (Van Esbroeck et al., 2015); however, recent literature suggests that tile drains are also a critical source of P, particularly in macroporous soils (Macrae et al., 2007a; King et al., 2014; Smith et al., 2015b; Sharpley et al., 2015).

Tile drains are perforated pipes that are used beneath agricultural soils to artificially improve soil drainage and lower the water table, increasing rooting depth of crops as well as promoting productivity. Similar to surface runoff events, tile drainage events are episodic, hydrologically responsive to precipitation or snowmelt events and can transport effluent across all seasons. Tan et al. (2002) found that over 65% of tile drainage and surface runoff occurred between November and March in southern Ontario during the non-growing season, and tile drains accounted for 30% of total precipitation inputs. Tile activation and time-to-response in drainage tiles is correlated with antecedent soil conditions (Geohring et al., 2001).

Runoff events in both surface and subsurface/tile sources can displace large amounts of P after manure or fertilizer application, which can account for a large portion of a field or catchment's annual P export (Pionke et al., 1996; Smith et al., 1998; Geohring et al., 2001; McDowell et al., 2001; Motavalli and Miles, 2002). In a study by Pionke et al. (1996) in Pennsylvania, the authors found that 70% of dissolved reactive-P export from runoff was derived from intense summer storms that produced the highest concentrations of P, which accounts for only 10% of the days in year. Storm flow was also found to be the main driver of P-export, particularly with events that produced surface runoff and sediment export (Pionke et al., 1996; McDowell et al., 2001; Hansen et al., 2002).

2.3 Factors governing Tile hydrologic and biogeochemical responses

2.3.1 Hydroclimatic Controls

Tile drains generally only export effluent and P during hydrological events where large inputs activate flow after hydrological thresholds, such as antecedent soil moisture, water table or infiltration capacity, have been satisfied. The thresholds that trigger flow in drainage tiles is a function of rainfall magnitude and intensity or snowmelt, antecedent soil moisture, soil type, surface cover, topography and land management practices (Macrae et al., 2007a; King et al., 2014; Kleinman et al., 2015a; Sharpley et al., 2015).

Antecedent soil moisture has been tied to runoff ratios and runoff responses in both surface runoff and tile drains (Pauwels et al., 2001; Scipal et al., 2005; Zehe et al., 2005; Wei et al., 2007; Brocca et al., 2009; Macrae et al., 2010; Radatz et al., 2013). High soil moisture content increases the hydraulic connectivity between the soil surface and tile drains, whereas inputs into soils with low soil moisture content will replenish the soil water content deficit, but will not generate drainage events until the threshold soil moisture is met. This threshold is generally near the field capacity of the soil, when the soil water storage potential is low (Kung et al., 2000a, 2000b; Macrae et al., 2010). Therefore, antecedent differences in soil moisture play a role in understanding tile flow and the timing of P-export over the course of a year in loam soils. Conversely, in heavily textured agricultural soils with high macropore connectivity and vertical cracking, preferential transport can mobilize large amounts of P (Kleinman et al., 2009; Reid et al., 2012; Fisher, 2014; Smith et al., 2015a).

2.3.2 Seasonality

Seasonal differences in P-export and tile drain hydrology exists, much of the literature discusses the difference between stormflow and winter hydrological processes (i.e. snowmelt) that result in the export of P on agricultural landscapes.

Storm flows in tile drains occur when precipitation or snowmelt events trigger a response. Precipitation events can have differing durations and intensities, which may result in differing P-losses in tile drains. High intensity (thunderstorm) events are more likely to export particulate P, as rain-splash erosion will factor into the losses. Many studies found storm flow to be the main driver of P-export (Sharpley et al., 1995; Pionke et al., 1996; Smith et al., 1998; McDowell et al., 2001; Hansen et al., 2002).

The non-growing season and winters create vastly different hydrological conditions that affect field hydrology and P-export. Cold region climates can experience greater snowmelt runoff than rainfall runoff such that snowmelt events become a major contributor to soil erosion and P-export (Hansen et al., 2000). For example, over 50% of annual total P export from an agricultural area in Ontario were derived from winter processes (Macrae et al., 2007a, 2007b) and ~80% in Manitoba (Liu et al., 2013). However, the amount of P-loss is likely dependent on the type of snowmelt, rain-on-snow events, and the presence of ice layers (Macrae et al., 2007b). Winter processes and snowmelt will have to be considered when Best Management Practices (BMPs) are being adopted to reduce non-point fertilizer and manure pollutants and prevent eutrophication (Bechmann et al., 2005; Messiga et al., 2010; Singh et al., 2009; Tiessen et al., 2010).

During the winter months, frost can also modify tile infiltration and thus P-export (Cade-Menun et al., 2013), prompting larger and more rapid response from rainfall or snowmelt due to the impeded permeability of the soil surface, where water input on frozen soil can result in very high runoff ratios (Shanley and Chalmers, 1999). Frozen ground is also more prone to soil erosion during runoff events, winter applications of fertilizer and manure risk greater P-losses, becoming detrimental to water quality (Bechmann et al., 2005; Liu et al., 2014). Frost depth and thickness is inversely correlated to the size of the snowpack, as the snowpack acts as an insulator to the soil. A thick snowpack can also slow response times; dampening peaks and reducing runoff ratios as the snow ripens during melt. However, midwinter melts, common in southern Ontario, often limit the thickness of end-of-season snowpack, contributing to discharge throughout the winter months (Haupt, 1967; Shanley and Chalmers, 1999; Macrae et al., 2007b).

2.4 Field conditions Influencing P movement into Tiles

When considering BMPs in fields with drainage tiles, it is important to understand how P losses and speciation is derived and how measurement practices affects losses. The following section discusses three factors that affect the export of P into drainage tiles: (i) macropores, (ii) P-stratification and (iii) crop residue.

2.4.1 Macropores

Macropores act as channelized preferential flow pathways found in soils; these pathways and networks contain hydrologically conductive properties that can be orders of magnitude higher than the surrounding soil matrix. The presence of macropores is an important aspect of soil characteristics when considering soil aeration as well as the ability of a soil to transport water, nutrients (particulate and soluble) and pollutants through the soil profile (Beven and Germann, 1982; Buttle and House, 1997; Gerke, 2006). Most soils contain macropore features to some extent, these features are often well established and are easily distinguishable in the soil profile. Even though macropores generally only exist as a small fraction of the total pore volume in a soil (0.5% – 5%), a small number of macropores can increase the flux saturation density of a soil by an order of magnitude in soils that have poor to moderate soil matrix conductivity (Beven and Germann, 1982; Kneale, 1985; Buttle and McDonald, 2002; Cameira et al., 2003).

Macropores created by soil fauna and flora are known as biopores that are cylindrical and tubular in shape. Soil fauna activity, particularly that of earthworms, is generally densest in the upper layers of the soil profile; they can be created by borrowing insects or by soil flora through living or dead/decaying plant roots. Macropores can also be created via soil cracking in heavily textured/clayey soils, forming vertical fissures that also have very high hydraulic conductivities (Beven and Germann, 1982; Buttle and McDonald, 2002; Reid et al., 2012).

Water travelling through macropores has very little interaction chemically with the surrounding soils due to the relatively small surface area and the high rates of flow compared to matrix-flow nutrients in water flowing through macropores have much fewer opportunities to be re-sorbed into the soil matrix and can therefore be very efficient in transporting P from the surface into the soil profile or towards tile drains (Beven and Germann, 1982; Hansen et al., 2002; Bouma, 1981; Newman et al., 2004; Shipitalo et al., 2000). Although this potential exists, it is unclear how often maropores are active or inactive, and how this varies temporally or spatially.

2.4.2 P-stratification in the Soil Profile

Phosphorus-stratification of soils occurs when fertilizer application on the soil surface is not incorporated into the soil via plough mixing, resulting in a high concentration of P and organic matter in the very top layer of the soil. P-stratification also occurs in natural systems as part of the decomposition process (Eckert and Johnson, 1985; Hansen et al., 2000; Messiga et al., 2010). This stratification of P increases the risk of dissolved P transport during surface runoff events such as large rainstorms and during spring snowmelt as well as erosion of P-rich soils on the soil surface (Sharpley, 2003; Ulén, 2010). Surface runoff can also rapidly transport P from P-stratified soils into macropores and tile drains, exporting dissolved P at much higher rates compared to runoff percolating through the soil matrix (Beven and Germann, 1982; Newman et al., 2004).

2.4.3 Crop residue on Agricultural Soils during the Non-growing Season

Retaining crop residues (e.g. stalks, leaves, etc.) on the soil surface during the non-growing season can be a BMP for erosion control. Crop residue reduces the amount of bare soil that is exposed to the elements and can therefore reduce the export of particulate P from agricultural soils that administer these practices, particularly during snowmelt and large rainfall events. Crop reside can also increase the hydrological conductivity of the surface, improving infiltration rates and reducing overland flows (Rahm and Huffman, 1984; Singh et al.. 2009; Kay and VandenBygaart, 2002). However, crop residue left on the soil surface has also been linked to nutrient leaching and the export of dissolved P as the plant matter decomposes (Schreiber and McDowell, 1985; Kay and VandenBygaart, 2002). Tillage methods that retain surface crop cover are excellent at reducing particulate P losses through the prevention of soil erosion; through this practice (in conjunction with P-stratification) may increase soluble P-export. The literature suggests than preventing dissolved P export is much more difficult when compared to preventing soil erosion (McDowell and Sharpley, 2001; Messiga et al., 2010).

2.5 Impact of Tillage Methods on P-Movement

Tillage methods are often used as BMPs to reduce P export from agricultural fields. The type of tillage method used often has advantages and disadvantages for reducing P-export, broadly relating to macropores, P-stratification and the presence of crop litter or cover crops. Management practices used on a particular farm field through differing tillage practices will affect soil physical and hydrological properties, and change the ability of the soil to retain (or export) P through leaching/runoff transport or erosion (Rahm and Huffman, 1984; Smeck, 1985; Hansen et al., 2002; Ulén, 2010). The next sections will describe and contrast three tillage practices that are common to North America: (i) conventional tillage, (ii) no-till, and (iii) conservation tillage.

2.5.1 Conventional Tillage

Conventional tillage includes the use of ploughing (e.g. mouldboard plow), which inverts the topsoil (to ~30 cm depth) to create a homogeneous layer as well as secondary tillage practices (e.g. disking) to level the soil and prepare the seed bed. Conventional tillage is often associated with the loss of valuable soil organic matter and erosion of topsoil, which also increases P-export. Ploughing leaves the fields bare after harvest and destroys existing soil structures and aggregates, exposing soils to erosional processes (e.g. wind, runoff, rainsplash, etc.) particularly during the non-growing season (Sharpley et al., 1995). Ploughing in conventional tillage allows the incorporation of P in crop litter and fertilizers throughout the Ap/plow layer, and prevents P-stratification of the surface after fertilizer is added, which can potentially reduce the amount of surface P that is leached during overland flow events. Macropores are also disrupted in conventionally tilled soils, reducing the density of macropores and the amount of runoff and P that can be preferentially transported from these fields in the seasons following tillage. However, conventional till systems risk surface and subsurface soil compaction and surface crusting, generally reducing the ability of water to infiltrate and increasing runoff and P exports, though this is temporally variable. Over the past several decades, there has been a shift by North American farmers away from conventional tillage to no-till and conservation till methods as a result of environmental sustainability as well as economic motivations, as moldboard plowing also requires intensive field-time-capital investments (Rahm and Huffman, 1984; Wade and Kirkbride, 1998; Ulén, 2010). The 2011 Census of Agriculture reported farms in Ontario that use conventional tillage method continues to decrease from previous census results, from 44% in 2006 to 37% in 2011 (Statistics Canada, 2011).

2.5.2 No-Till

No-till fields are not ploughed, and seeds are inserted into the soil directly with no preparation of the seedbed. This field management practice is thought to be better at preventing soil erosion and reducing the risk of soil surface sealing and compaction, as there is minimal soil manipulation or disturbance. No-till fields are best able to preserve soil structure and aggregates, generally improving the infiltration and percolation of water, though this can take >5 years to achieve (Rahm and Huffman, 1984; Stevens et al., 2009; Ulén, 2010). Crop residue is left on the field after harvest as cover, reducing soil erosion during the non-growing season. Crop residue also improves hydraulic conductivity, improving the water storage capacity and soil moisture retention of the soil (Lampurlanés and Cantero-Martínez, 2006; Ulén, 2010). The increased organic matter in the uppermost soil layer will also promote biological activity on the farm field. The cumulative effect of no-till soils is a healthier soil where particulate P losses can be vastly reduced compared to conventional tillage methods (Lampurlanés and Cantero-Martínez, 2006; Ulén, 2010). However, because no-till soils are never worked, no-till fields can increase the transport of water and soluble P through the soil at much higher rates as a result of preferential pathways (macropores) and P-stratification, bypassing the soil matrix. This can increase dissolved P export values into tile drains as the accumulation of P in the top 5 cm of soil on no-till fields have been found to be up to 3 – 5 times greater than conventional till (Cameira et al., 2003; Bertol et al., 2007). Indeed, macropores are more established and extensive in NT soils because of the lack of disturbance in the top 30 cm. Phosphorus stratification is enhanced in NT because soils are not mixed. Thus, increased soil P stratification plus enhanced connectivity can increase P loss to tiles. As a result, managers are recommending BMPs where tillage is used to incorporate P and break up pores as was the case around Lake Erie (Macrae et al., 2007a; Michalak et al., 2013; King et al., 2014; Smith et al., 2015a; Sharpley et al., 2015).

2.5.3 Conservation Tillage

Conservation tilled fields receive a less aggressive till on fields compared to conventional till such that by definition, at least 30% of crop residue cover is retained on the soil surface and soils are not inverted (Rahm and Huffman, 1984; Djodjic et al., 2005; Ulén, 2010). Both no-till and rotational till are forms of conservation tillage, rotational tillage is a common form of tillage method with minimum disturbance used in Ontario and there is very little agricultural lands that use no-till throughout the crop rotation as a BMP (O'Halloran, Macrae, English, Pers. Comm.) Conservation tillage practices where tilling is minimal or eliminated after harvest allows crop residue to remain on the field during winter months. Tilling is reduced to approximately once every three years. This greatly reduces soil erosion, particle transport and total P losses through surface and subsurface runoff (Rahm and Huffman, 1984). This tillage practice is also better at preventing soil erosion from wind and water compared to conventional tillage. Similar to no-till, the hydraulic conductivity and water storage capacity of conservation till soils is better than that of a conventional till since this tillage practice preserves soil aggregates and promote water infiltration reducing particulate transport and P-export. Moreover, the minimal tillage conducted through conservation tillage can disrupt some of the surface macropores that would be more prevalent in no-till fields, reducing soluble P-export through preferential pathways. As well, this method of tillage also incorporates the fertilizers into the soil, reducing the surface P-stratification and risk of DRP losses during flow events. However, the potential for particulate P losses in conservation till system is greater than that of a no-till system

(Rahm and Huffman, 1984; Djodjic et al., 2005; Ulén, 2010). Thus, conservation tillage or rotational tillage may be an improved BMP for minimizing P-loss in tile drains.

2.6 Thesis Objectives

The objectives of this thesis are to:

1) Quantify year round losses of runoff, DRP and TP losses from drainage tiles beneath annual disk till (AT) and rotational conservation tillage (RT) plots,
2) Investigate the role of seasonality (particularly winter snowmelt) on runoff and P losses
3) Characterize temporal differences in subsurface runoff generation and P export in tile drainage,
4) Determine if the hydrologic and biogeochemical responses of tile drains in a sandy loam soil can be predicted from simple, easily monitored hydrometric data.

Objectives 1 and 2 are addressed in “Effects of tillage practices on phosphorus transport in tile drain effluent under sandy loam agricultural soils in Ontario, Canada” (Chapter 3 of this thesis). While, objectives 3 and 4 are addressed in “Seasonal and event-based drivers of runoff and phosphorus export through agricultural tile drains under sandy loam soils in a cool temperate region” (Chapter 4).

Chapter 3 – Effects of Tillage Practices on Phosphorus Transport in Tile Drain Effluent under Sandy Loam Agricultural Soils in Ontario, Canada

3.1 Abstract

Agricultural watersheds have been identified as a source of nutrients to surface water bodies, contributing to the degradation of water quality. Reduced till (RT) management practices have been employed to reduce the potential for particulate P loss in surface runoff, but may increase the transfer of dissolved reactive phosphorus (DRP) into tile drains. It is unclear if RT increases P losses in tile drainage when nutrient management strategies are used and fertilizers are applied in the subsurface. It is also unclear how these management strategies perform year round, including during the snowmelt period. The objectives of this study are to quantify year round losses of runoff, DRP and total phosphorus (TP) losses from drainage tiles beneath annual disk till (AT) and reduced till (RT) plots, and, to investigate the role of seasonality (particularly winter snowmelt) on runoff and P losses. Results indicate that both runoff and P-export were episodic across all plots and most annual losses occurred during a few key events under heavy precipitation or snowmelt events. Runoff and P losses through drainage tiles were primarily observed between October and May, with most losses occurring in March during snowmelt. Tillage practices did not affect DRP or TP concentrations or loads in tile drainage. This study has highlighted the importance of the non-growing season (particularly winter) in annual P loss, and has demonstrated that the cumulative Best Management Practices (BMPs) used at the study sites may be an effective way to reduce P losses in tile drain effluent.

3.2 Introduction

The eutrophication of surface water bodies is a global issue. Surface water bodies that undergo eutrophication experience increases in macrophytes and phytoplankton biomass, and occasional harmful algal blooms (HABs) that are detrimental to ecosystem health. Algal blooms often lead to oxygen being utilized by bacteria during the algal decomposition process, causing oxygen deficiency, anoxia and fish kills (Bennett et al., 2001; Cloern, 2001; Howarth and Marino, 2006). Elevated phosphorus (P) concentrations in freshwater lakes have been identified as the primary contributor to more frequent HABs in many North American lakes such as Lake Winnipeg in Manitoba, Canada (Schindler, 2012) and Lakes Erie and Simcoe in Ontario, Canada (Evans et al., 1996; Winter et al., 2007; LEEP, 2014). Consequently, the reduction of P loads to freshwater lakes has been identified as a priority issue in many regions across North America.

Despite efforts to reduce P loads to freshwater lakes in North America, P loads to many lakes such as Lake Erie appear to be increasing, and the occurrence of HABs has been increasing in frequency over the past decade (Kane et al., 2014). Much of the P loads are now derived from non-point sources (Carpenter et al., 1998; LEEP, 2014; Kleinman et al., 2015b; Smith et al., 2015a), which are difficult to control. Some of the elevated P loads to lakes have been attributed to changes in climate, particularly increased rainfall (Bennett et al., 2001; Filippelli, 2002; Messiga et al., 2010; Bosch et al., 2013), but some have been attributed to changing agricultural management practices in surrounding watersheds (Bosch et al., 2013;

Michalak et al., 2013), leading managers to re-evaluate the efficacy of Best Management Practices (BMPs) (*e.g.* Smith et al., 2015a; Kleinman et al., 2015b).

Phosphorus mobilization in agricultural watersheds has been historically viewed as a surface water issue due to the ability of subsoils to adsorb or filter P in percolating water (e.g. Sample et al., 1980). Consequently, reduced tillage has been widely recommended as a BMP to reduce sediment loads into tributaries via surface runoff from agricultural lands (Rahm and Huffman, 1984; Sharpley et al., 1995; Djodjic et al., 2005; Ulén, 2010).

There is mounting evidence that suggests that tile drains beneath agricultural lands are a significant source of P to tributaries (Macrae et al., 2007a; King et al., 2014; Smith et al., 2015b; Sharpley et al., 2015) although this appears to vary with soil characteristics (Fisher, 2014; Kleinman et al., 2015a). Tile drainage systems are networks of perforated pipes installed under agricultural fields that aid in removing excess water from the soil profile during periods of high water input such as large and persistent precipitation events as well as during snowmelt (Johnsson and Ludin, 1991; Tan et al., 1993). Both dissolved and particulate forms of P have been shown to move into tile drains in landscapes where there are significant macropore networks, or in soils with little remaining P sorption capacity, suggesting that tile can therefore increase P loss from agricultural fields (Bouma, 1980; Beven and Germann, 1982; Beachemin et al., 1998; Stamm et al., 1998; Tan et al., 1998; Jarvis, 2007; Fisher, 2014).

Recent work suggests that the transport of dissolved reactive P (DRP) into drainage tiles is enhanced under no-till (NT) management practices used in conjunction with surface application of P attributed to increased stratification of P in surface soils (Sharpley, 2003; Bertol et al., 2007; Ulén, 2010; Fisher, 2014; Kleinman et al., 2015a) and enhanced macropore networks (Beven and Germann, 1982; Tan et al., 1998; Jarvis, 2007). The stratification of P in the soil profile may also enhance P loss in surface runoff. Indeed, the increased DRP concentrations in Lake Erie have been partially attributed to the increased adoption of reduced tillage (RT) practices (Michalak et al., 2013), leading to the re-evaluation of NT and RT as BMPs. Much of the existing knowledge on enhanced DRP loading in tile drainage under NT management has been conducted at the southwestern end of Lake Erie, where heavy textured clay soils and tile drainage are prevalent, but less is known regarding the effects of NT on P-mobilization in tile drainage from loam soils, which are found throughout much of Ontario, away from the southwestern end of Lake Erie (OMAFRA, 2007). Moreover, little edge-of-field data exists to characterize whether or not NT or RT management enhance P loss in tile drain effluent when used in conjunction with subsurface P placement (or the incorporation of P). Furthermore, much of the scientific understanding of P loss in tile drainage and the effects of management practices has been developed from data collected during the ice-free season, and has not included the winter period or snowmelt, despite the fact that this is a critical period for runoff in the Great Lakes region and other regions that experience cold winter periods with significant snowfall. To our knowledge, no studies have evaluated the effects of RT management on P loss in tile drains in the Great Lakes region of North America during the winter months, when more than 50% of the annual P-loss occurs in Ontario (Macrae et al., 2007a, 2007b).

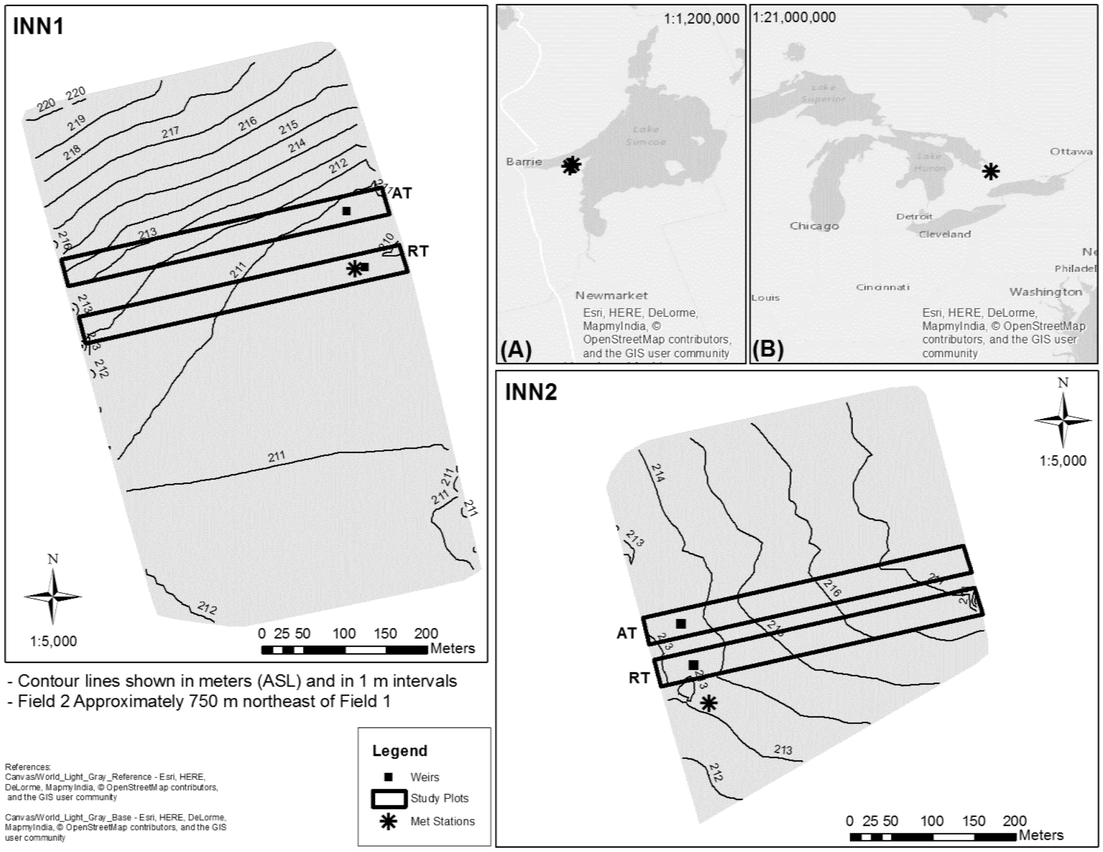

Figure 3.1: Map of the study fields (INN1, INN2) and plots (AT, RT) in the Lake Simcoe watershed (Inset A) in the Great Lakes region of Ontario, Canada (Inset B). Field topography is shown in grey (contour interval 1 m). The location of the meteorological station and tile monitoring stations are shown.

Improved understanding of the effects of RT on P mobilization in tile drains effluent is highly relevant to producers across Ontario and in other regions with similar climate and soil types.

Lake Simcoe (44°25'N 79°20'W) is the largest lake in southern Ontario excluding the Great Lakes with a surface area of 722 km^2 and it is a shallow dimictic hard-water lake (Evans et al., 1996). The watershed feeding into Lake Simcoe is 3,557 km^2 in total area and supplies drinking water to eight municipalities, where

47% of the watershed is agricultural. The lake has faced problems with P-loading and eutrophication since the 1970s and anthropogenic activities have tripled the amount of P loading since pre-settlement values, resulting in destructive levels of algae and aquatic macrophytes growth (HABs) that have resulted in cold-water fish recruitment failure (Evans et al., 1996, Winter et al., 2007). Winter et al. (2007) suggest that water quality has improved slightly in the past decade, and P-loading into Lake Simcoe has been reduced compared to amounts in the 1980s and 1990s. However, in order to re-establish self-sustaining cold-water fish stocks, late-summer hypolimnetic dissolved oxygen levels must be increased, and thus, further P load reductions are necessary. The use of BMPs such as RT may be a way to achieve these further reductions by limiting agricultural non-point sources. However, it must first be determined if P mobilization in tile drain effluent is enhanced under reduced till management systems. Thus, the specific objectives of this study are: (1) quantify runoff and concentrations and loads of DRP and total P (TP) in tile drain effluent from agricultural fields in the Lake Simcoe Watershed and characterize seasonal patterns; and, (2) to determine if runoff volumes and/or P mobilization or speciation differ among plots under annual disk till (AT) or RT (rotational vertical tillage) tillage practices.

3.3 Methods

3.3.1 Site Description

Research for this study was conducted in two adjacent fields (INN1 and INN2), located in Innsifil, Ontario, directly south of Kempenfelt Bay in Lake Simcoe (Figure

3.1). Average annual precipitation in the region is 933 mm, with 22% of precipitation falling as snow. Moderated by the effects of the Great Lakes, long term (30-yr) daily mean temperatures are -7.7 °C in January and 20.8 °C in July, demonstrating a climate of warm summers and cool, snowy winters, where mid-winter thaws are fairly common in the region (Environment Canada, 2013b).

Soil types at the site are of the Grey-Brown Luvisol Great Group and of the Bondhead and Guerin series (sandy loam) (Hoffman et al., 1962). These soils are very stony and range from imperfectly drained to having good drainage. In both soil series, surface soil consists of dark greyish brown A_1 and A_2 horizons that grade to a light grey, with more clay-rich B horizons found at approximately 60 cm (Hoffman et al., 1962). Below the B horizon, soils are light grey, calcareous loam and sandy loam tills (Hoffman et al., 1962). The INN2 field is smooth and flat (Slope: 0.5%), whereas the INN1 field is moderately sloped (Slope = 1.5%) (Figure 3.1). Soils of the Guerin series (present at the downslope end of INN1) are imperfectly drained compared to those in the Bondhead series (found at the upslope end of INN1 and across all of INN2). Tiles are found at a depth of approximately 1 m below the soil surface, and are systematically spaced 40 ft (~12.2 m) apart. Tiles run perpendicular to the slope on INN1.

INN1 was established in December 2010, and data collection commenced in February 2011. INN2, located approximately 300 meters northeast of INN1, was established in August 2011, with sample commencing immediately. The fields are managed in the same way (same landowner, management and crop types) and under corn-soybean-winter wheat rotation, but are staggered in their rotation

(INN1: Corn (2010), soybeans (2011), wheat (2012); INN2: soybean (2010), wheat (2011), corn (2012)). Both fields have been under a minimum rotational till for more than a decade (shallow 2" vertical tillage after winter wheat harvest in July/August). Both fields typically receive commercial fertilizers (190 kg/ha of 14-14-11-13 NPKS fertilizer for winter wheat, applied in fall with seed, or 165 kg/ha 15-10-9-15 NPKS for corn, applied in spring, 2x2 beside seed), both applied via bands (subsurface P placement). No fertilizer is applied prior to soybeans. Both winter wheat and corn crops are side-dressed with nitrogen and potash (20-0-5, 350 L/ha and 460 L/ha, respectively) in May to provide a total of approximately 120 and 150 kg N/ha. Approximately 43 kg P_2O_5/ha is applied over the entire crop rotation. During the study period, P was applied in October 2011 for INN1 (prior to winter wheat) and in April 2012 (prior to corn) for INN2. The sites differ in their surface (0-15 cm) soil test P, with 25 mg/kg Olsen-P at INN1, 5 mg/kg at INN2.

Two 30 m wide plots were located within each field, centered along a central, single tile line. Within each plot, the contributing area to the central tile was assumed to be 50% of the distance to the adjacent tiles (total width of 12.2 m), and plots extended along the entire tile, which spanned the length of the field (250 m). Plots were located 60 m apart, separated by 5-6 tile lines, to minimize lateral movement of effluent from one plot to the next. Both fields had a baseline period where water samples were collected prior to the implementation of tillage differences. During this period, all plots were managed under RT practices (vertical tillage following wheat, prior to corn planting the following spring: completed in fall 2009 at INN1, fall 2011 at INN2). Within each field, one plot was aggressively tilled (disk harrows, 4" depth) in April 2012 (INN2) and August 2012 (INN1) and the other plot was managed in the same manner that has traditionally been done at the sites (vertical tillage in August 2012, INN1; August 2011, INN2). The period of baseline data collection allowed the characterization of natural spatial differences in subsurface runoff characteristics between the plots, as well as the influence of slope at INN1 prior to the introduction of the different tillage methods as a new variable.

3.3.2 Field Methods

Within each plot, tile drains were intercepted at the field edge (below ground) to capture edge-of-field losses for the study plot. A 10° v-notch weir box was installed and connected to the 6" plastic corrugated drainage tile pipe, allowing the tile water to enter and exit the weir box freely. Water depths in weirs were recorded using pressure transducers (Onset HOBO-U20-001-04), accuracy +/- 0.3 cm), corrected using barometric pressure), monitored at 10-minute intervals, year round. During exceptionally high peak flow events, water levels in field and the weir boxes exceeded the depth of the weir. Tile flow during these periods was corrected using a stage-discharge relationship developed over several months using a Hach Flo-tote 3 depth and velocity sensor placed in the weir boxes, connected to a Hach FL900 data logger and also recorded at 10-minute intervals. Individual hydrologic events occurring over the study period were identified based on tile flow responses, initiating with a rise in the tile hydrograph and ending with a subsequent return to baseflow conditions.

Discrete water samples were collected from each tile using automated water samplers triggered by tile runoff (Teledyne ISCO). Sampling intervals were generally 6 – 12 hours during the winter/spring months and 2 – 6 hours during the summer/fall months, when tile flow responses were typically shorter in duration. The objective of the variable sampling strategy was to achieve full coverage of the hydrograph, including the rising limb, peak flow and falling limb. Samples collected were largely event-based, although periodic baseflow samples were also collected. Samples were composited for selected events to achieve greater spans of sampling. Field samples were retrieved and filtered within 24-48 hours of collection during warm periods and within 3-5 days during winter events. All flow and water quality monitoring equipment was housed inside an enclosure at each plot to minimize the freezing of equipment and weir during the winter months. Heating of enclosures was not necessary and freezing was only observed during exceptionally cold periods when tiles were not flowing. As such, this method was found to be a robust approach to monitoring tile drainage in winter conditions in this region.

A meteorological tower was located within each field. Both towers measured air temperature and relative humidity at 1.0 m and 3.0 m height (Vaisala HMP45C), net radiation (Kipp & Zonen NR-LITE), as well as wind speed and direction (R.M. Young 05103). The met-tower at INN1 was also equipped with a tipping bucket rain gauge (Texas Electronics TE525M) and a pressure transducer for weir water level measurements (Campbell Scientific CS450). Meteorological data was recorded at 30-minute intervals using a Campbell Scientific CR-1000 data logger.

Estimates of snowfall were obtained from a nearby weather station in Barrie, ON (Station ID: 611056; Environment Canada, 2013a). Data obtained online was validated using manual snow surveys at the sites prior to thaws. An array of 3 soil probes was installed within each plot to measure soil temperature and moisture at 10, 20 and 70 cm depth (Decagon Devices Inc. 5TM SM/Temp sensors with EM-50 data logger, Onset Ltd.).

3.3.3 Laboratory Methods

Retrieved samples were immediately processed for the determination of P species. A 50 mL subsample was filtered using 0.45 μm cellulose acetate filters (Delta Scientific), refrigerated and analyzed within 1-2 weeks of collection for DRP content. A second, unfiltered subsample was acidified to 0.2% H_2SO_4 (sulfuric acid), and subsequently digested (Kjeldahl digestion method, Seal Analytical Hot Block Digestion System BD50) for the determination of TP. Samples were analyzed for P content using ammonium molybdate/ascorbic acid colorimeteric methods (Bran-Luebbe AutoAnalyzer III system, Seal Analytical, Methods G-103-93 (DRP), G-188-097 (TDP, TKP), detection limit 0.001 mg/L P). A small subset of samples (~10%) were also tested for total dissolved P, where filtered (0.45 μm) samples were acidified and digested using the same method as TP. Approximately 5% of all samples were analyzed in replicate and found to be within 5% of reported values.

3.3.4 Statistical Analyses

Data in this study did not meet the assumption of normality. Consequently, non-parametric statistical analyses were used. The effects of season on runoff volumes and P loads were tested using a series of one-way Analysis of Variance (ANOVA) tests. To account for potential natural differences among plots in the study fields, the effects of tillage practices on runoff and P loss were tested using a Shearer-Ray-Hare test (non-parametric equivalent of a two-way ANOVA) (Calvin and Dytham, 1996) using Plot (each of the plots on the fields) and Treatment (prior to or following the tillage treatment) as factors, where a significant interaction effect between Plot and Tillage was assumed to indicate that tillage of one of the two plots per field significantly changed the relationship between the two plots. Relationships between event magnitude and P loss or P concentration were investigated using regressions. Effects were accepted as significant at $p<0.05$.

3.4 Results

3.4.1 Meteorological conditions over the study period

Total annual precipitation amounts received in 2011 (945 mm, 17% as snow) and 2013 (987 mm, 57% as snow) were typical of long-term 30-year means for the region (933 mm, 22% as snow, Environment Canada, 2013b); however, 2012 was a significantly drier year (748 mm, 15% as snow) (Figure 3.2a).

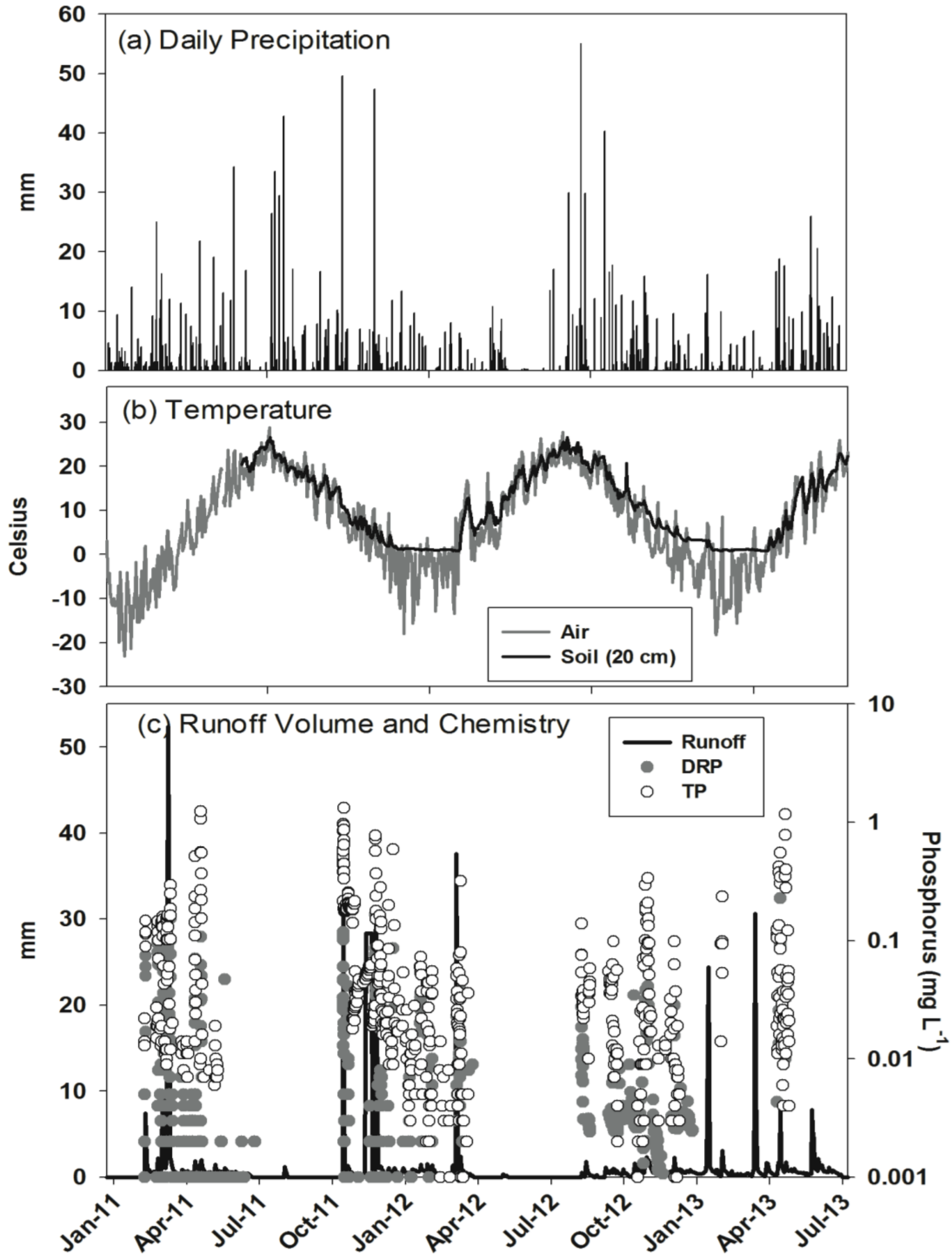

Figure 3.2: (a) Daily precipitation (rain shown with grey bars, snow shown with black bars); (b) Mean daily temperature in air (grey line, measured 1 m above ground) and soil (black line, measured at 20 cm depth); and (c) runoff (black line, left y axis) and DRP (grey circles) and TP (white circles) concentrations in discrete samples from the RT plot in the INN1 field.

Seasonal distributions of precipitation varied among the study years. Precipitation received in 2011 was evenly distributed throughout the year, which is typical of long-term averages for the region (Environment Canada, 2013b). In contrast, only 63% of the normal precipitation was received January – May of 2012, and, 50% in June - July. Cumulatively, this resulted in 206 mm (59%) below average precipitation for a significant portion of 2012. Precipitation volumes received between August and December 2012 were typical for the region (Figure 3.2a, Environment Canada, 2013b). In contrast, in 2013, above average precipitation (349 mm rain + 207 mm snow) was received January – June.

Air temperature over the study period varied seasonally, with annual maxima in summer and minima in winter (Figure 3.2b). Both of the summers in the study period (JJA) were slightly warmer than the average temperature of 19.2 ˚C (19.8 °C in 2011 and 20.3 °C 2012). Temperatures during the winters (JFM) of 2011 (mean = -7.6 °C) and 2013 (mean = -4.4 °C) were typical of the long-term means (-5.8 °C), whereas 2012 was considerably warmer (mean = -0.6 °C). Both winter seasons during the study period spanned between November and March; however, frequent thaw events were experienced in both years. There were 20 individual events of mid-winter thaw (spanning a total of 51 days) with daily mean temperatures above 0 ^{o}C between December and March inclusive in 2011-2012. In 2012-2013, there were 16 thaw events, spanning over a total of 37 days. Soil temperatures at 20 cm depth reflected patterns in air temperature, with dampened temperature fluctuations (Figure 3.2b). Soil temperatures followed atmospheric temperatures more closely in summer than in winter when there was snow cover.

Soil temperatures at 20 cm depth approached freezing temperatures (~1 – 2 ^{o}C) throughout January – March, but did not freeze over the study period.

3.4.2 Runoff in Drainage Tiles

Approximately 220 mm runoff was exported via the drainage tiles in 2011 (22% of precipitation), 121 mm in 2012 (16% of precipitation), and 229 mm between January and June 2013 (41% of precipitation) (runoff estimates expressed are means across all plots and sites). Much of the annual tile runoff occurred during discrete events, and tiles did not flow during drier periods (Figures 3.2c, 3). Runoff via drainage tiles from all four plots demonstrated similar temporal patterns (Figure 3.3), and runoff responses coincided with rain or snowmelt events (Figure 3.2c). Although drainage tiles were highly responsive to precipitation inputs, hydrologic responses were variable both among individual events and seasonally (Figure 3.2c, 3).

Twenty-seven individual hydrologic events (up to 2.8 L/s flow rate in 6" tiles) were observed over the study period: 10 in 2011, 11 in 2012 and 6 events in the first half of 2013, spanning across a total of 143 days over the 852 day study period (17%). Baseflow (approximately 0.5 L/s; ~0.0002 mm/d) or dry conditions (*i.e.* no flow) were experienced over the remaining 83% of the study period. Seasonal and event-based distributions of runoff in tiles were variable among the study years. Tiles were generally hydrologically active throughout the fall, winter and spring (Figure 3.2c). Numerous winter events (*e.g.* mid-winter thaws, rain-on-snow, and the freshet) were observed in each of the study years. In all three years, the main freshet occurred in mid-March, and represented one of the largest annual hydrologic events (including 2012, which was an anomalously low snowfall year). Baseflow was observed throughout the winter periods, even in the absence of thaw events, whereas tiles generally did not flow in either of the two summer periods and baseflow was not observed during these periods (Figure 3.2c). The duration of the summer dry period was longer in 2012 (May through October) than in 2011 (July through September), which is consistent with rainfall received (Figure 3.2a). Runoff events that occurred during the summer were triggered by heavy thunderstorm events; however, these runoff responses were small and short in duration, and were not followed by a period of baseflow as was observed at other times of year. Hydrologic activity (*i.e.* baseflow and frequent rainfall responses) recommenced in approximately October/November of the study years (Figure 3.2, 3.3). A one-way ANOVA found that the magnitudes (mm) of individual events differed with season [$F(3,92)=25.009$, $p<0.001$], with significantly larger events occurring in winter or fall versus those occurring in spring or summer ($p<0.02$); whereas differences were not observed among winter and fall events ($p>0.05$) or spring and summer events ($p>0.05$). An ANOVA testing for differences in the magnitudes of events occurring prior to and following the implementation of the Treatment (i.e. tillage on one of the two plots on each field) did not reveal significant differences in event size at INN1 [$F(3,1)=0.007$, $p=0.932$] or INN2 [$F(3,1)=2.795$, $p=0.105$].

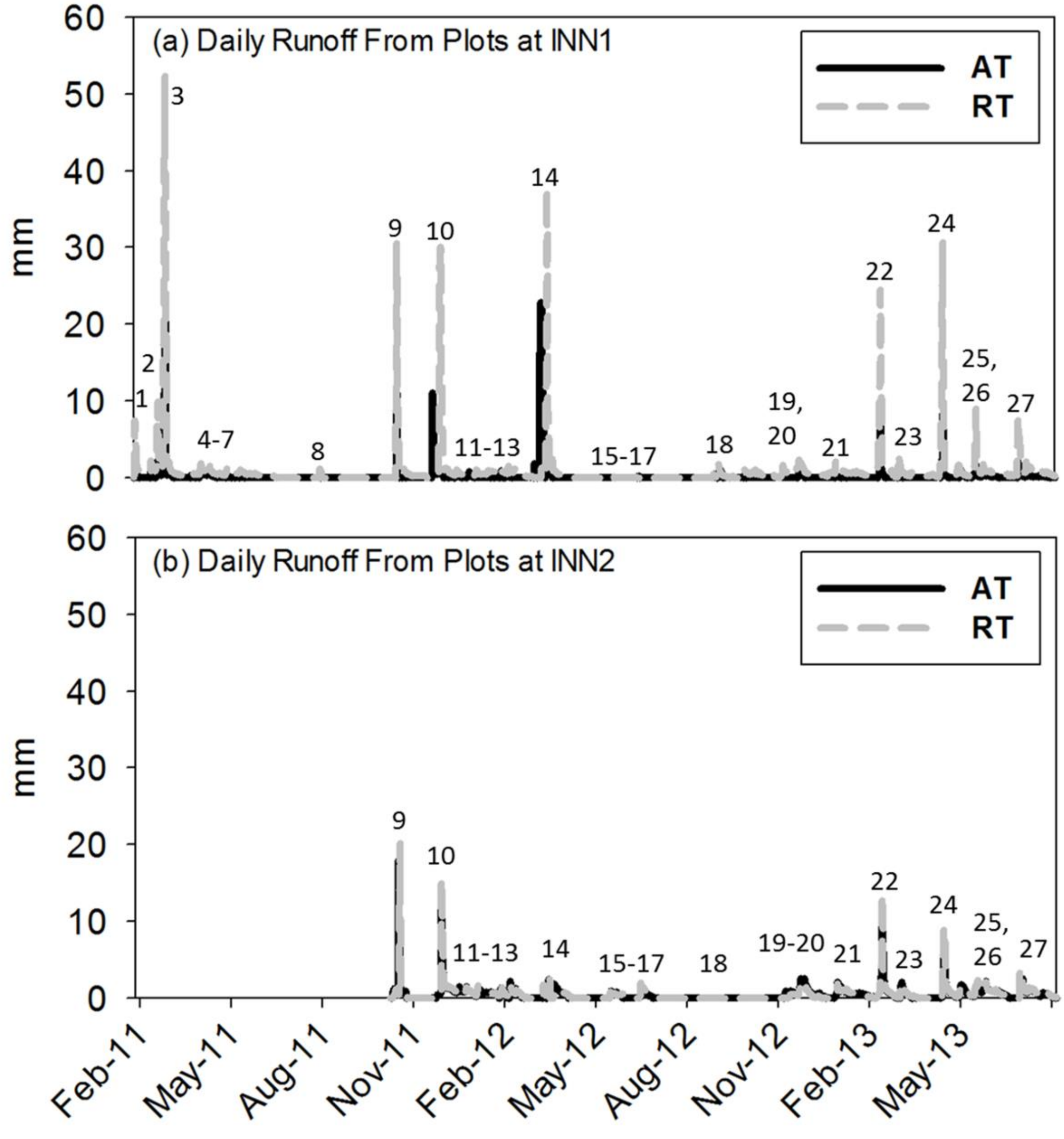

Figure 3.3: Daily runoff from two adjacent tile drains (RT and AT plots) in the INN1 (a) and INN2 (b) fields. Individual events characterized over the study period are labeled numerically in the figure and correspond with events described in Figures 3.4 and 3.5.

Although the plots in this study exhibited similar temporal responses, some spatial variability was observed amongst the tile plots (Figure 3.3). At INN2, the RT plot was slightly more hydrologically responsive than the AT plot, (Figure 3.3, Table 3.1), but differences were restricted to high flow events (Figure 3.3) and were not observed during smaller events. Consequently, significant differences in event-related runoff (mm) among the plots were not observed [$F(1,32)=0.008$, $p=0.928$]. Spatial differences among plots were more apparent at INN1, which had a sloping topography. The RT plot, located downslope of the AT plot, was consistently more hydrologically responsive than the AT/upslope plot (prior to and following the annual tillage treatment) (Figure 3.3, Table 3.1). This was observed during both high and low flow events throughout the study period [$F(1,49)=12.137$, $p=0.001$]. Two-way ANOVAs using Plot and Treatment (*i.e.* prior to or following the tillage of one of the two plots) as factors did not produce significant interactions, suggesting that tillage did not affect event-related runoff volumes.

3.4.3. Spatiotemporal Variability in Phosphorus Transport in Tile Drain Effluent

Instantaneous water samples collected from the four tiles throughout the study period demonstrated strong variability throughout and among individual events, and, between baseflow and event responses (*e.g.* Figure 3.2). During periods of low flow or baseflow,

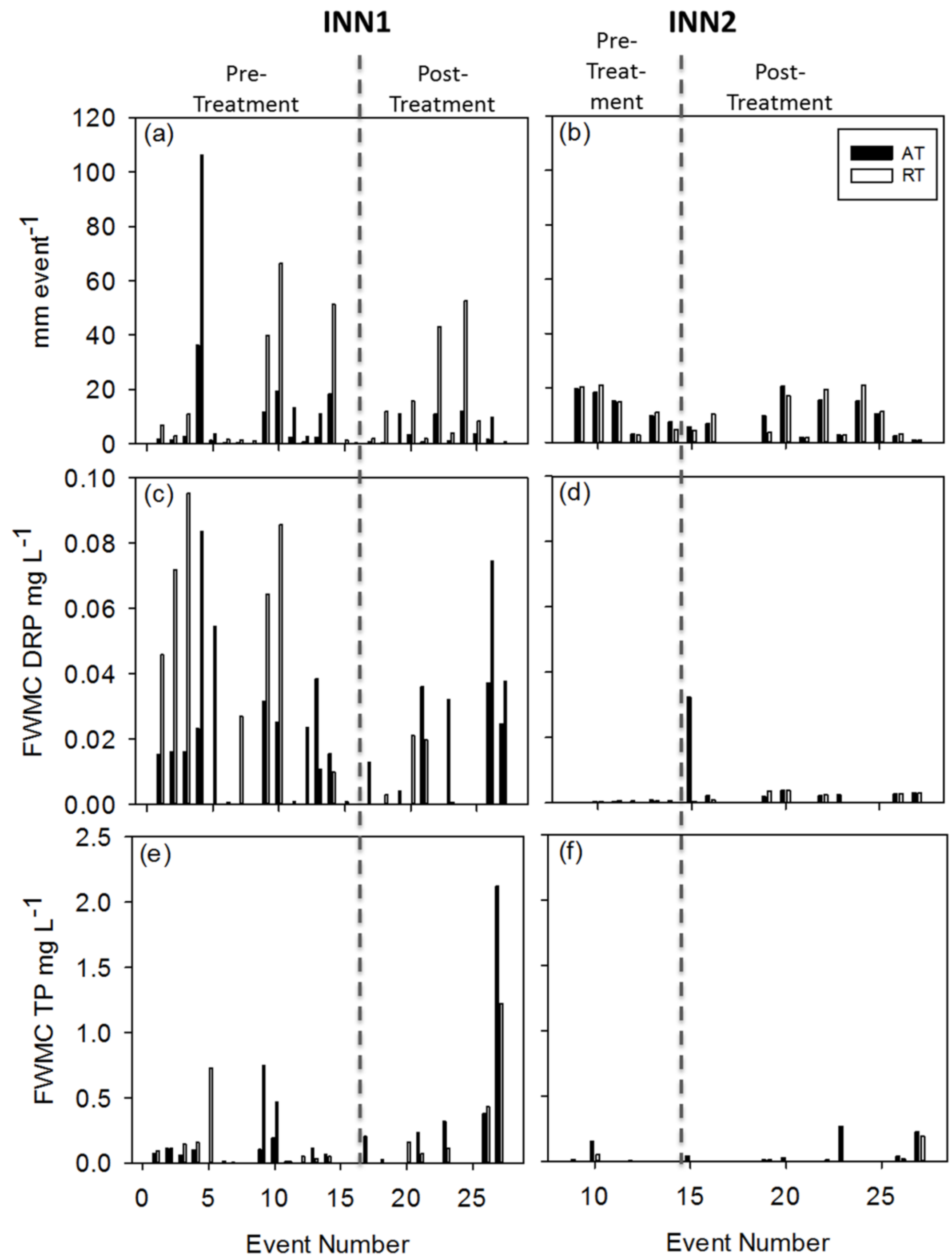

Figure 3.4: Runoff (a,b), flow-weighted mean DRP concentrations (c,d) and flow weighted TP concentration (e,f) from the AT (black) and RT (grey) plots for 27 individual events captured over the study period from INN1 (a,c,e) and INN2 (b,d,f). The implementation of the tillage treatment on the AT plot is shown with a hatched grey line in each plot. Prior to this point, both plots were RT. Events captured correspond with those labeled in Figure 3.3.

TP and DRP concentrations were generally <0.01 mg□L, with very little difference between TP and DRP concentrations. (DRP:TP = ~0.8) (Figure 3.2c). This was observed for all tiles (not shown). Elevated DRP and TP concentrations coincided with discharge peaks (Figure 2c). Dissolved reactive P concentrations ranged from 0.005- 0.225 mg/L during events, typically falling between 0.05-0.15 mg/L during peak flow. Event-based instantaneous TP concentrations ranged from 0.007-1.316 mg/L, with peak TP concentrations generally falling between ~0.10 – 0.50 mg/L (Figure 3.2c).

Flow weighted mean concentrations (FWMC, i.e. normalized for discharge) of DRP and TP (Figure 3.4) and DRP and TP loads were calculated for individual events (Figure 3.5) occurring over the study period. The magnitudes of individual events (mm) were positively related to DRP loads [$F(1,63)=22.544$, $p<0.001$, $R^2=0.264$] and TP loads [$F(1,57)=20.925$, $p<0.001$, $R^2=0.256$], but not $FWMC_{DRP}$ [$F(1,68)=3.022$, $p=0.087$, $R^2=0.028$], or $FWMC_{TP}$ [$F(1,64)=1.908$, $p=0.172$, $R^2=0.029$]. A series of one-way ANOVA tests did not reveal significant seasonal differences in $FWMC_{DRP}$ or $FWMC_{TP}$ ($p>0.05$). When data from both fields were pooled, it was found that DRP:TP ratios did not differ with season. However, when the fields were tested separately, a weakly significant effect of season on DRP:TP ratios in event-related FWMC was found at INN1 [$F(3,1)=3.123$, $p=0.039$], caused by lower DRP:TP ratios in spring ($p=0.048$) and fall ($p=0.087$) compared to winter.

The distribution of total DRP and TP loads (events and baseflow included) in seasons throughout the study years is shown for INN1 (Table 3.1).

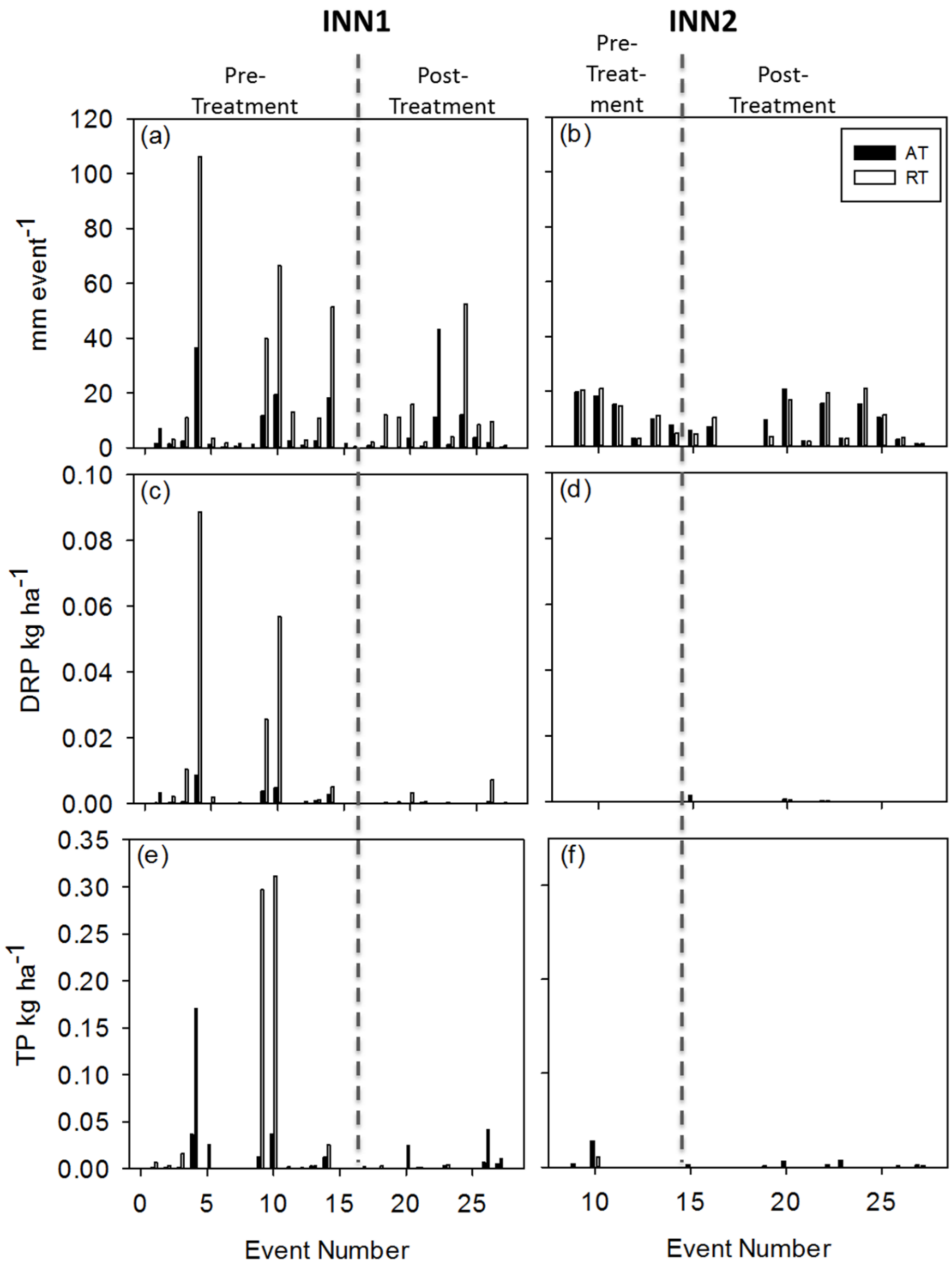

Figure 3.5: Runoff (a,b), DRP loads (c,d) and TP loads (e,f) from the AT (black) and RT (grey) plots for 27 individual events captured over the study period from INN1 (a,c,e) and INN2 (b,d,f). The implementation of the tillage treatment on the AT plot is shown with a hatched grey line in each plot. Prior to this point, both plots were RT. Events captured correspond with those labeled in Figure 3.3.

Table 3.1: Seasonal and annual breakdown of precipitation, discharge from tiles, runoff ratios (discharge/precipitation), dissolved reactive phosphorus and total phosphorus loads in tiles, and ratios of DRP:TP are shown for 2011, 2012 and the first half of 2013. The two plots from INN1 are shown. The plots were both under reduced tillage (RT) management from 2011-August 2012. After August 2012, Plot B was disk tilled as part of the annual till (AT) management. This period is shown in *italics.* Values are expressed in the units indicated and as [% of annual total] beside each value.

	Precip. (mm)	Discharge (mm)		Runoff Ratio		g DRP/ha		g TP/ha		DRP:TP	
		Plot B *(AT)*	Plot C (RT)	Plot B (AT)	Plot C (RT)	Plot B (AT)	Plot C (RT)	Plot B (AT)	Plot C (RT)	Plot B (AT)	Plot C (RT)
JFM	207 [22]	47.6 [49]	154.6 [44]	0.23	0.75	9 [52]	104 [55]	41 [45]	196 [23]	0.23	0.53
AMJ	214 [23]	8.9 [9]	54.9 [16]	0.04	0.26	< 1 [<1]	3 [1]	< 1 [0]	27 [3]	0.58	0.10
JAS	250 [26]	0.1 [0]	2.7 [1]	0.00	0.01	0 [0]	0 [0]	0 [0]	5 [1]	0.06	0.07
OCD	273 [29]	39.7 [41]	140.2 [40]	0.15	0.51	9 [48]	83 [44]	49 [55]	609 [73]	0.17	0.14
2011	944 [100]	96.2 [100]	352.3 [100]	0.10	0.37	18 [100]	190 [100]	90	837	0.20	0.23
JFM	155 [21]	28.6 [72]	98.7 [53]	0.19	0.64	4 [78]	7 [57]	16 [66]	32 [45]	0.24	0.22
AMJ	67 [9]	0.3 [1]	1.4 [1]	0.01	0.02	< 1 [1]	< 1 [0]	1 [3]	0 [0]	0.06	0.73
JAS	321 [43]	*4.9 [12]*	21.7 [11]	*0.02*	0.07	*< 1 [4]*	1 [8]	*3 [12]*	12 [17]	*0.07*	0.08
OCD	205 [27]	*5.8 [15]*	63.3 [34]	*0.03*	0.31	*1 [17]*	5 [35]	*5 [20]*	27 [38]	*0.18*	0.17
2012	748 [100]	*39.6 [100]*	185.1 [100]	0.05	0.25	*5 [100]*	13 [100]	*24 [100]*	72 [100]	*0.21*	0.18
JFM	286	*29.7*	141.9	*0.10*	0.50	*5*	27	*3*	4	*0.20*	0.41
AMJ	269	*17.5*	86.6	*0.07*	0.32	*1*	8	*12*	53	*0.07*	0.15

Phosphorus losses for both P species followed the same distribution patterns as runoff losses, where the largest loads of P occurred during the shoulder seasons of spring and fall and corresponded with large flow events (Table 3.1, Figure 3.5). Annual DRP losses (average of both plots) were 104 g/ha and 9 g/ha for INN1 for 2011 and 2012, respectively, and 3 g/ha for INN2 (2012). Annual TP losses (average of both plots) were 464 g/ha and 48 g/ha for INN1 (2011, 2012) and 7 g/ha for INN2 (2012). Most of these losses occurred during a few events each year, when both flow and P concentrations were elevated (Figure 3.4, 3.5). The winter and snowmelt period (JFM) accounted for 52-78% of annual losses for DRP and 23-66% of TP losses (Table 3.1). This largely occurred during the freshet in March. The winter (JFM) and autumn (OND) periods combined accounted for 84-87% of annual runoff, and 95 – ~100% of the annual DRP losses and 86 – 99% of annual TP losses. Thus, in both study years, a small fraction of the annual P loss occurred throughout the growing season (Table 3.1). $FWMC_{DRP}$ for events on INN2 increased slightly following the application of commercial P (concurrent with the timing of the implementation of the tillage treatment on the AT plot for that field). A two-way ANOVA using Plot and Treatment as factors found a significant difference in $FWMC_{DRP}$ among events prior to the application of P and implementation of tillage treatment [$F(3,1)=32.200$, $p<0.001$) for the INN2 site. There was not a significant interaction between the effects of Plot and Treatment on $FWMC_{DRP}$ [$F(3,1)=0.445$, $p=0.511$] indicating that the impacts of the fertilizer applied to both plots at the timing of the treatment implementation were experienced by both plots and did not change with tillage. The effects of treatment were not significant at the INN1 field (p=0.629). In contrast to INN2, the tillage treatment at INN1 was not done concurrently with P application. DRP concentrations were, however, elevated at INN1 (both plots) between January - March 2011 (Figure 3.4c) and, elevated during the autumn of 2011 compared to autumn 2012 (commercial P was applied in October 2011 on this field).

Median and (range) flow-weighted mean concentrations of DRP for individual events over the study period (all data collection on each field pooled) were higher at INN1 [Median = 0.016 mg/L (0.001 – 0.095 mg/L)] than at INN2 [Median = 0.001 mg/L (<0.001 – 0.032 mg/L)] [t(91)=-27.376, p<0.001]. Similarly, flow-weighted TP concentrations were lower at INN2 [Median = 0.012 mg/L, <0.001 – 0.271 mg/L)] than at INN1 [Median = 0.104 mg/L, 0.003 – 2.120 mg/L] [t(92)=27.376, p<0.001]. These differences (summarized in Figure 3.6) reflect the greater soil P concentrations at INN1 (~25 mg/kg) relative to INN2 (~5 mg/kg).

Flow-weighted DRP concentrations (Figure 3.4c,d) appeared to be larger at the RT plot (downslope plot) at INN1, relative to the AT plot (upslope plot); however, this was primarily restricted to the early and latter parts of the study period and was not consistent across all events. ANOVAs testing for differences with Plot, did not find significant differences in $FWMC_{DRP}$ or $FWMC_{TP}$ between study plots on INN1 or INN2 (p>0.05) when all events occurring throughout the study period were pooled for each field. A two-way ANOVA using Plot and Treatment as factors did not find significant interactions between the effects of Plot or Treatment on $FWMC_{DRP}$ or $FWMC_{TP}$ at INN1 or INN2 (p>0.05), suggesting that tillage did not affect DRP or TP loss on either field. Event based $FWMC_{DRP}$ and $FWMC_{TP}$ events are summarized (Figure 3.6) between INN1 and INN2 and by plot (prior to and post tillage treatment). Although it appears that there were $FWMC_{TP}$ increased at the AT plot in INN1 following implementation of the tillage treatments (Figure 3.6), the difference was not significant at the 0.05 level

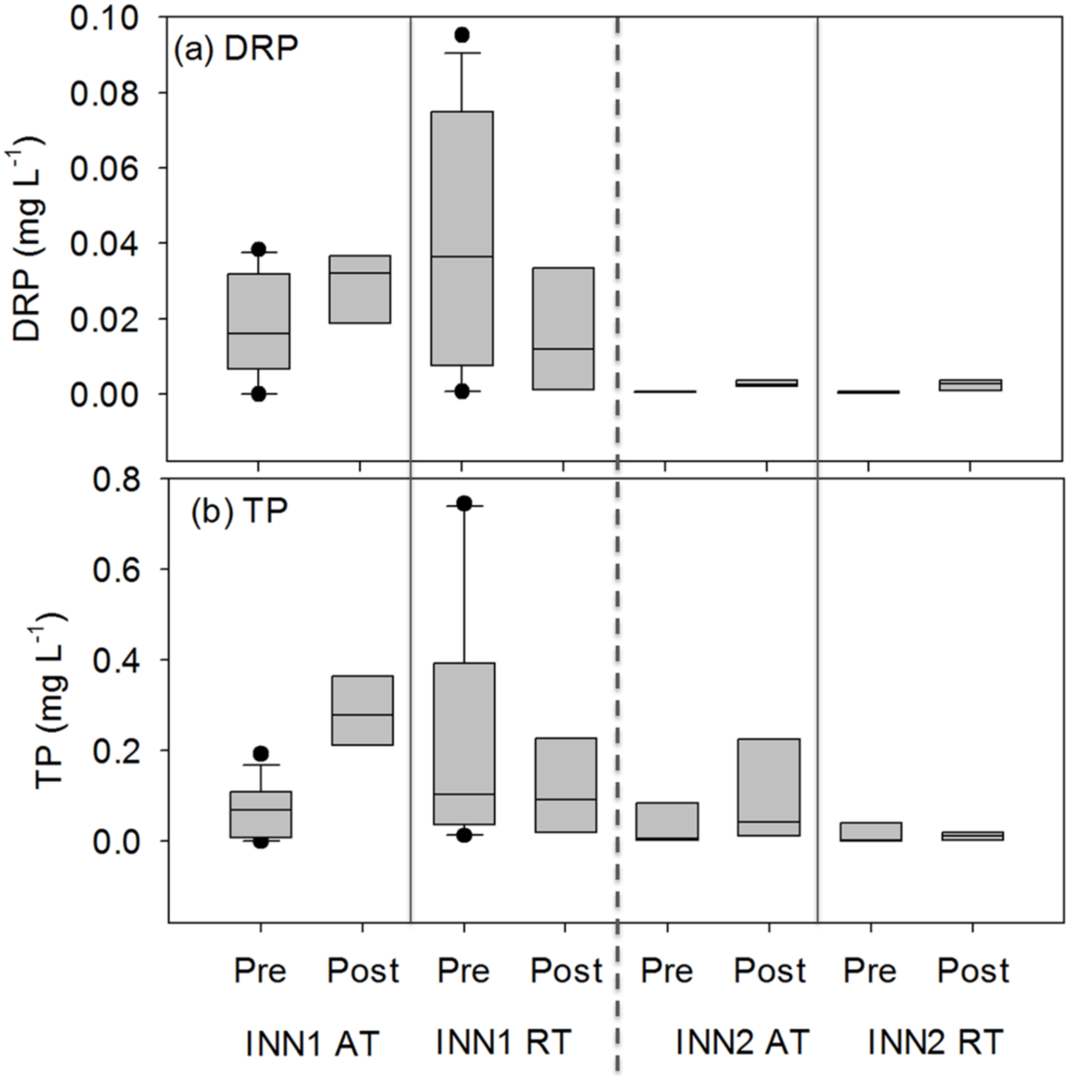

Figure 3.6: Box-whisker plots of flow weighted mean concentrations of DRP (a) and TP (b) for all events captured before and after the tillage treatments were implemented. Boxes show the 25th, 50th and 75th percentiles and whiskers show the 10th and 90th percentiles. Outliers are shown with black circles. Whiskers are not shown on some of the boxes as the 10th and 90th percentiles could not be generated for the small number of events observed during the uncharacteristically dry season.

3.5 Discussion

Annual runoff and P losses were low from the study sites in comparison to what has been observed elsewhere in the literature. Annual losses of P in tile drainage ranged from 3-104 g DRP/ha and 7-464 g TP/ha. These rates are considerably lower than what has been observed in the Great Lakes region of Canada and USA. Studies in Quebec by Eastman et al. (2010) and Jamieson et al. (2003) saw 0.3-2.3 kg/ha/yr in subsurface TP losses and 0.0982 kg/ha TP during snowmelt respectively.

Although losses in surface runoff were not monitored, surface overland flow rarely occurs at the study sites. Thus, P loss from these sites is likely low overall. The low rates of P loss are due in part to small runoff losses in general, but also low P concentrations in tile drain effluent. Previous studies have suggested that approximately 40% of precipitation inputs to fields are exported via tile drainage (*e.g.* Macrae et al., 2007a; King et al., 2015). In this study, 10-37% of precipitation was lost via tiles during a year receiving average precipitation, and only 5-25% in a drier year that received only 80% of the average annual precipitation. Dissolved reactive P and TP concentrations were also low in comparison to what has been observed by others in tile drain effluent (*e.g.* Sims et al., 1998; Gentry et al., 2007; Macrae et al., 2007a; Vidon and Cuadra, 2011; Smith et al., 2015a, 2015b).

Nearly all of the P loss (>99%) was associated with event-related flow (*e.g.* storms and/or thaw). The significance of storm events to P loss in tile drainage has also been observed in other studies (Pionke et al., 1996; McDowell et al., 2001; Hansen et al., 2002). In the current study, the three largest events in 2011 accounted for 62% of the total annual discharge from INN1, occurring over only 11 days (of a total of 201 days of flow in 2011). The contribution of the same three events to annual P loss was 91% DRP and 94% TP. This further demonstrates how episodic P loss is in tile drainage, and highlights the need to capture such variability in models.

Elevated P concentrations were generally observed on the rising limb of the tile hydrograph, and, P concentrations were very low during baseflow conditions and during the latter portion of events (receding limb of hydrograph). This is consistent with what has been observed elsewhere in this region (*e.g.* Macrae et al., 2007a), and is attributed to prevalence of matrix flow rather than preferential transport via macropores under such flow conditions (Flury et al., 1994; Kleinman et al., 2009). Indeed, the significance of macropores to P transport into drainage tiles appears to become more problematic in more heavy textured soils compared to the soils at this study site (Fisher, 2014; Kleinman et al., 2015b). It is also important to note, however, that the study sites were under *reduced* tillage management rather than NT. Indeed, the development of macropores may have been minimized by periodic vertical tillage. Thus, periodic (minimal disturbance) till may be an effective management strategy to break up the macropores that may facilitate P loss to tile drainage.

Interannual variability in precipitation amounts and timing lead to very different runoff volumes from the sites, which also lead to lower losses of P in tile drain effluent. Anomalously low precipitation quantities were received throughout the winter, spring and summer of 2012 compared to long-term norms for the region (Environment Canada, 2013b). Higher than average temperatures (4.6 ˚C above normal) along with a large number of daily average temperatures above zero, resulted in less snowfall overall, and a small end-of-season snowpack. Collectively, these conditions lead to a small snowmelt compared to 2013, which had a more typical winter period. The small spring runoff in 2012 also resulted in lower runoff amounts throughout the spring and summer of 2012. The generally drier conditions in 2012 also affected P export from the drainage tiles, reducing P loss. For example, the RT plot on INN1 RT exported 53% of the discharge produced in 2011, but only 7% of total P-export.

3.5.1 Importance of seasonality and weather events to runoff generation and phosphorus loss via tile drainage

Over the study period, most runoff and P loss occurred during the winter and autumn months, and was entirely associated with storm or thaw events rather than baseflow. This seasonal runoff pattern is typical of Southern Ontario (*e.g.* Macrae et al., 2007a, 2010), although wet summer seasons occasionally occur (Environment Canada, 2013a, 2013b). The timing of runoff and P loss demonstrated in this study highlights the importance of capturing this period in sampling programs, and also demonstrates the need to have an improved understanding of cold-weather (especially snowmelt) processes when attempting to predict and prevent P losses in tile drain effluent.

Snowmelt events are often a major contributor to both soil erosion and P-export in agricultural landscapes in cool regions (e.g. Hansen et al., 2000). Snowmelt was shown to export 20% of annual TP-export in an eastern Canada study (Su et al., 2011), ~50% in a Southern Ontario study (Macrae et al., 2007a) and ~70% in a

Manitoba study (Prairie climate) (Liu et al., 2014). In the current study, snowmelt contributed approximately half of the annual tile runoff yield and >52% of the annual DRP and >23 % of the annual TP export. The relative importance of the snowmelt period in annual P loss demonstrates the importance of employing BMPs that are effective through the winter period. Many existing BMPs that use vegetation (*e.g.* riparian buffer strips, catch crops) have been shown to be less effective in cold climates because freeze-thaw cycles lead to the release of DRP from dying vegetation (e.g. Bechmann et al., 2005; Tiessen et al., 2010; Ulén et al., 2010; Liu et al., 2013, 2014). Nutrient management and P application rate, placement and timing may be more effective BMPs.

In the current study, most precipitation events during the summer months did not produce a tile hydrologic response, and precipitation went into soil storage or lost to evapotranspiration. However, large precipitation events that exceed the storage capacity of the soil matrix produced tile drain responses in summer, although the tile flow responses were much smaller and short-lived than was observed at other times of year for comparable rainfall amounts. This is in contrast to what has been observed in heavier textured soils that are prone to shrinkage and cracking (Bouma, 1980; Djodjic et al., 2000; Macrae et al., 2007a; King et al., 2015), where summer rainfall can be rapidly routed into drainage tiles via cracks that act as preferential drainage pathways (*e.g.* Sims et al., 1998; Stamm et al., 1998; Reid et al., 2012; Smith et al., 2015a).

Although some subtle differences were observed, clear, consistent seasonal patterns in P speciation in tile drain effluent were not observed. DRP:TP ratios appeared to be greater in winter and fall and lower in spring and summer. The lower TP concentrations in winter compared to summer likely result from the fact that snowmelt lacks the kinetic energy of rainfall, leading to less erosion of particulate material (Tiessen et al., 2010). Particulate losses in summer may also have been elevated in comparison to winter conditions as a result of the breakdown of soil aggregates by wet-dry cycles. Although elevated DRP losses during the winter period may be derived from crop residue left on the soil surface, as freeze-thaw cycles can result in a significant increase of soluble P release from both soil and vegetation (Formanek et al., 1984; van Klaveren and McCool, 1998; Bechmann et al., 2005; Singh et al., 2009; Messiga et al., 2010; Tiessen et al., 2010; Liu et al., 2013, 2014), $FWMC_{DRP}$ were not significantly higher in winter than during other periods of year when data from both years and fields were pooled. However, $FWMC_{DRP}$ for events occurring on INN1 during the winter of 2011 appeared to be larger. This may have resulted from corn residue from the previous season.

3.5.2 Natural spatial variability in runoff and phosphorus loss within and between sites

There were differences in both runoff patterns and P loss within and among the sites. These patterns were present prior to the tillage treatment and therefore represent natural variability at the site. The INN1 field is moderately sloped, and soil on the field transitions between the Bondhead soil series at the upslope end of the field to the Guerin soil series at the topographically lower end of the field. The two soil series are very similar, but the Guerin series is imperfectly drained relative to the Bondhead series (Hoffman, 1962). The INN2 field is entirely of the Bondhead series and is flat. Drainage across the two sites reflected these differences, where the AT plot on INN1 (upslope plot) and all plots on the INN2 field produced less runoff and flowed less continuously than the RT plot (slope bottom) on INN1 (Figure 3.3). The tile drains on the INN2 field also produced less runoff than the upslope plot (AT) on INN1, despite being in a similar soil series.

There were also differences in P concentrations in tile drain effluent between the two sites. DRP concentrations were much smaller in effluent from INN2 than INN1 (Figure 3.6). It is likely that this is a reflection of the differences in soil test P between the two sites (25 mg/kg Olsen-P at INN1, 5 mg/kg at INN2), as P concentrations in runoff have been shown to increase with soil test P concentrations. Differences in soil test P between the two sites may have been derived from natural heterogeneity or from differences in historic nutrient application patterns, which can result in long-term elevated concentrations of phosphorus runoff (Haynes and Williams, 1992; McDowell et al., 2001; Sharpley et al., 2001; Wang et al., 2012a). Indeed, differences in tile drainage DRP concentrations were more apparent than differences in TP concentrations (Figure 3.4). The reduced P loss under lower soil P concentrations highlights the importance of nutrient management strategies. A reduction in P application rates and soil test P may be an important means to reduce P loading from agricultural lands. At the study sites, P is applied at a rate that takes crop usage into consideration. These small P application rates do not appear to be at the expense of crop yields at this site. Crop yields at the sites over the study period were 82 bushels/acre (soy), 82-89 bushels/acre (winter wheat) and 142 bushels/acre (corn), which are fairly typical for the region, located at the northern edge of southern Ontario.

During the baseline data collection period (when tillage treatments were the same across plots), no differences in DRP or TP concentrations in effluent were observed at INN2. However, although no significant effect of Plot was observed at INN1 when all events were pooled, the topographically lower tile drain had higher concentrations of DRP than the upslope tile (Figure 3.4) during large events in the study period (but not smaller events). This was also observed for TP during some events (Figure 3.4e), but to a smaller extent than what was observed for DRP (Figure 3.4c). These enhanced P concentrations at the downslope plot may be from both crop residue and surface soil, and likely occur due to enhanced connectivity between the surface and tile drains via macropores, which occurs under wetter conditions in loamy soils (Kung et al., 2000). These natural differences within a site, even between "paired" plots, demonstrate the importance of a baseline data collection period prior to the implementation of a treatment.

3.5.3 Impacts of tillage practices on runoff and phosphorus loss via tile drainage

Tillage did not lead to a difference in DRP or TP concentrations in tile effluent at either site. Prior to the AT treatment, the low slope plot on INN1 had larger DRP concentrations relative to the upslope plot. In 2012, both prior to and following tillage on the AT plot, there were no differences in P concentrations between the two plots. However, 2012 was a much drier year than 2011. Thus, the lack of differences between the two tiles in 2012 may be a function of reduced flow overall, which would have lead to less connectivity between the surface and the tile via macropores in the RT (downslope) plot. Although the main snowmelt event in 2013 was unfortunately missed by our autosamplers, the topographic differences in DRP concentrations between the two tiles were once again apparent during the late March/early April storms (Figure 3.2c). In spite of the fact that significant differences in P concentrations were observed between plots at INN2 following tillage, the effects of Treatment were apparent on both the RT and AT plot, suggesting that the elevated concentrations were the effect of P application rather than tillage.

The lack of differences in P mobilization into drainage tiles between tillage treatments is in contrast to what others have shown (Rahm and Huffman, 1984; Djodjic et al., 2005; Ulén, 2010). Indeed, much of the recent increases in DRP loading to Lake Erie have been attributed to increased adoption of NT management systems, particularly in the Maumee watershed (Cameira et al., 2003; Michalak et al., 2013). The lack of differences between tillage treatments is likely due to a combination of factors. First, rotational vertical tillage may break up the macropores that develop under NT systems, lessening the potential for preferential drainage into tile drains. Under a true NT management system, soils may exhibit greater P loss as greater macropore development could increase infiltration rates and connectivity between the surface and tile drains. Indeed, the preferential flow pathways prevalent in NT soils have been shown to increase hydrological transport and P loss (Rahm and Huffman, 1984; Cameira et al., 2003; Ulén, 2010). Second, P is not surface applied on the study fields and is instead applied in the subsurface at the time of seeding.

Subsurface placement of P may lessen the stratification of P on the soil surface, thereby lessening the concentration of P in runoff entering soil macropores (Sharpley, 2003; Bertol et al., 2007). Although surface runoff was not measured as part of the current study, subsurface placement of P may also reduce P loss in surface runoff by lessening the stratification of P in the soil profile that occurs when P is surface broadcast on NT soils (Sharpley, 2003; Ulén, 2010). Third, soils in the study fields are sandy loams. Although macropores exist in these soils, they are primarily due to biological activity (*e.g.* earthworms, roots) rather than as cracks caused by drying/shrinkage in clays. As such, loamy soils may be less sensitive to the impacts of tillage and/or fertilizer application on P mobilization in tile drainage.

3.5.4 Impact of phosphorus application on phosphorus loss in tile drainage

At the study sites, commercial P fertilizers are applied with the planter when planting corn and winter wheat. Consequently, P was applied to INN1 in October 2011 and INN2 in April 2012. Both DRP and TP concentrations in tile drain effluent were greater in the autumn of 2011, following P application, compared to the autumn of the subsequent year when P was not applied. It should be noted, however, that conditions were also drier in the autumn of 2012 than in 2011, which also may have led to the observed differences. On INN2, the first tile drain response following P fertilizer application produced elevated DRP and TP concentrations (0.001-0.012 mg/L DRP, 0.016-1.255 mg/L TP in fall 2011) in tile drainage from the AT plot, but this was not observed in the adjacent RT plot. Dissolved reactive P concentrations in tile drain effluent from INN2 were slightly elevated from both the

AT and RT plots throughout the remainder of the study period, but were still low overall (Figure 3.4d).

3.6 Conclusions

This study has provided year round estimates of P loss in tile drainage from two fields that use nutrient management strategies, rotational vertical tillage and subsurface P placement (in bands with seed). Tillage did not increase losses of P in tile drain effluent at either site, possibly due to the nutrient management and fertilizer application strategies employed. Phosphorus losses from these sites are low in comparison to what has been reported elsewhere in the literature. As such, this management system, and the combination of BMPs that it employs, may be an effective way to reduce P loss in tile drainage from agricultural lands. This study has also shown that that the winter period and the non-growing season in general are crucial periods for runoff and P loss and highlights the need to gain an improved understanding of winter processes. Given the strong seasonality in runoff trends in Ontario and comparable climates, it is imperative that BMPs selected for use in cool temperate regions will be effective during and following frozen conditions. These results also show that reduced tillage systems are not a problematic BMP for P loss in tile drains under all conditions. This suggests an improved understanding of the mechanisms of subsurface water and P loss under variable conditions is warranted.

Chapter 4 – Seasonal and Event-Based Drivers of Runoff and Phosphorus Export through Agricultural Tile Drains under Sandy Loam Soil in a Cool Temperate Region

4.1 Abstract

Frequent algal blooms in surface water bodies caused by nutrient loading from agricultural lands are an ongoing problem in many regions globally. Tile drains beneath poorly and imperfectly drained agricultural soils have been identified as a key pathway for phosphorus (P) transfer. Two tile drains in an agricultural field with sandy loam soil in southern Ontario, Canada were monitored over a 28-month period to quantify discharge and the concentrations and loads of dissolved reactive P (DRP) and total P (TP) in their effluent. This paper characterizes seasonal differences in runoff generation and P export in tile drain effluent and relates hydrologic and biogeochemical responses to precipitation inputs and antecedent soil moisture conditions. The generation of runoff in tile drains was only observed above a clear threshold soil moisture content (~0.49 $m^3 \bullet m^{-3}$ in the top 10 cm of the soil; above field capacity and close to saturation), indicating that tile discharge responses to precipitation inputs are governed by the available soil-water storage capacity of the soil. Soil moisture content approached this threshold throughout the non-growing season (October – April), leading to runoff responses to most events. Concentrations of P in effluent were variable throughout the study but were not correlated with discharge ($p>0.05$). However, there were significant relationships between discharge volume (mm) and DRP and TP loads (kg ha^{-1}) for events occurring over the study period ($R^2>=0.49$, $p=<0.001$). This research has shown that the hydrologic and biogeochemical responses of tile drains in a sandy loam soil can

be predicted to within an order of magnitude from simple hydrometric data such as precipitation and soil moisture once baseline conditions at a site have been determined.

4.2 Introduction

The long-term deterioration of water quality can lead to eutrophication and the loss of biodiversity and ecological function, which degrades the aesthetic and economic value of water bodies (Carpenter et al., 1998; Bennett et al., 2001; Sharpley et al., 2001; Filippelli, 2002). Phosphorus (P) has been identified as the limiting nutrient in the many North American lakes and receiving waters, and P loss from agricultural land has been identified as a major source of P to these water bodies (Sharpley et al., 1995; Correll, 1998; Filippelli, 2002; Ruttenberg, 2005; Schindler, 2006; Quinton et al., 2010). The careful management of agricultural P to reduce loads is necessary. Efforts have been made to reduce P losses from both urban and agricultural settings; however, frequent harmful algal blooms continue to occur despite these efforts (Evans et al., 1996; Winter et al., 2007; LEEP, 2014; Sharpley et al., 2015).

Surface overland flow has historically been recognized as the primary pathway for P loss from fields (Stamm et al., 1998; Macrae et al., 2010; van Esbroeck et al., 2016). However, artificial subsurface (tile) drainage beneath agricultural fields has more recently been identified as a major pathway for P transport (Macrae et al., 2007a; King et al., 2014; Smith et al., 2015b; Sharpley et al., 2015). There are trade-offs between having surface versus subsurface drainage from fields. Indeed, P concentrations may be smaller in tile drainage in comparison to surface runoff; however, tile drainage facilitates a greater volume of runoff from fields, with P prevalently in the dissolved (bioavailable) form (King et al., 2015a), and, tile drains eventually discharge directly into streams and tributaries, minimizing that potential for P retention in the landscape. Thus, P must be managed in a way that minimizes P loss in both the surface and subsurface environments.

Phosphorus concentrations in tile drainage have been shown to be elevated under some agricultural fields, but not all. Elevated P concentrations in tile drainage have been related to soil type, soil P content, tile drain depth and spacing, and have been shown to be particularly high beneath fields with well-defined macropores or preferential flow systems (i.e. cracks) that route P-rich water from surface soils into tile drains, bypassing the more sorptive soil matrix (Beven and Germann, 1982; Beachemin et al., 1998; Stamm et al., 1998; Tan et al., 1998; Goehring et al., 2001; Jarvis, 2007; Reid et al., 2012; Fisher, 2014), or, drainage systems connected to surface inlets (King et al., 2015). Elevated DRP losses in tile drainage have also been related to management practices such as no-till (which reduces the erosion of particulate P (PP) in surface runoff) and the broadcasting of P on the soil surface (King et al., 2015b), which leads to increased macropore density and soil P stratification (King et al., 2015b). Consequently, the continued installation of tile drains and the selection of appropriate Best Management Practices (BMP) for fields underlain by tile drains have become subjects of debate (Carpenter et al., 1998; Gentry et al., 2007; Smith et al., 2015b; Kleinman et al., 2015b). Recently, Lam et al. (2016) demonstrated that P concentrations were not elevated in tile drains under rotational, conservation till management systems when P was placed in subsurface bands and soil test P was maintained at modest levels.

Discharge has been shown to influence P concentrations in tile drains. Several studies showed that DRP, PP and TP concentrations are much higher during storm and high flow events compared to baseflow and decrease rapidly after peak discharge in the falling limb of the hydrograph (Stamm et al., 1998; Heathwaite and Dils, 2000; Gentry et al., 2007; Kinley et al., 2007; Williams et al., 2015). Williams et al. (2015) found that peak-flow concentrations of DRP in tile drains were up to an order of magnitude higher compared to baseflow. However, the same studies have shown that discharge-concentration relationships are often poor (Stamm et al., 1998; Kinley et al., 2007; Williams et al., 2015), and are not consistent among events or seasons (Stamm et al., 1998; Macrae et al., 2010; Williams et al., 2015). However, relationships between discharge and nutrient loads may be stronger. For example, in a study of 35 watersheds, Basu et al. (2010) concluded that annual stream discharge could be used as a surrogate to predict annual load export.

The majority of research in quantifying P transport in tile drains to date has been done in clay soils where cracking is prevalent. Less attention has been given to the hydrological and biogeochemical responses of tiles in coarser textured soils such as silt loams or sandy loams, which are often tile drained if they are imperfectly or poorly drained. There is a need to better understand how and why tiles in medium to coarser textured soil respond both hydrologically and biogeochemically given the extensive spatial coverage of these soil textures beneath agricultural lands in North America and elsewhere globally (Sims et al., 1998; McDowell et al., 2001). In addition, much of the existing knowledge surrounding P transport via tile drains has been obtained from research conducted throughout the growing season (GS) and little is known about hydrological and biogeochemical processes at other times of year. This may be problematic as the vast majority of both runoff and P loss in regions under cool, temperate climates occurs during the non-growing season (NGS) (e.g. Johnsson and Ludin, 1991; Tan et al., 1993; Macrae et al., 2007a, 2007b; Macrae et al., 2010; King et al., 2014; Lam et al., 2016; Van Esbroeck et al., 2016; King et al., 2016). It is unclear if and how both subsurface runoff generation processes and P transport differ between rainfall-driven events occurring during the growing season or spring/fall and the winter period (freeze-thaw cycles/snowmelt events).

Our ability to model and predict runoff and P loss in tile drainage is also lacking, particularly in winter (Gentry et al., 2007; Kleinman et al., 2015a; Sharpley et al., 2015). To predict hydrologic and biogeochemical losses in landscapes with agricultural tile drains, many models have been created (e.g. DRAINMOD, HYDRUS, HSFP, PLEASE, ICECREAMBD and SWAT), which vary in the processes accounted for, parameters considered, and their spatial and temporal scales (Radcliffe et al., 2015). There is considerable uncertainty associated with these models because processes related to both the supply and transport of P into tile drains are complex, and many of the parameters driving these processes remain poorly defined. Furthermore, with the exception of ICECREAMBD, many models are not designed specifically for the prediction of P loss from tile drains, and consequently face limitations in performance. The simplifications made by models, the quality and amount of data available to drive models, and natural variability in the landscape also contribute to the uncertainty associated with these models (Radcliffe et al., 2015). Despite these challenges, the evaluation and widespread adoption of BMPs and the setting of realistic, achievable targets for the reduction of P loads requires the use of models. An improved understanding of both hydrologic and biogeochemical responses in tile drains throughout an annual cycle, particularly the winter period, may provide useful metrics for predicting such losses, which can subsequently be used to develop and improve models (Hively et al., 2006; Kleinman et al., 2015a). Such an understanding may also shed insight into BMPs that are suitable for medium to coarser textured soils under cool temperate climates. The objectives of this study are 1) to assess seasonal differences in tile drain discharge and P losses; 2) to evaluate the relationship between discharge and P concentrations and loads; 3) to develop a simple regression model to predict tile discharge and P loads in sandy loam soils using precipitation and antecedent soil moisture measurements.

4.3 Methods

4.3.1 Site description

Research for this study was conducted in southern Ontario, Canada, in the Great Lakes region (Figure 4.1). The region has a humid continental climate with warm summers and cold, snowy winters (Koppen DFb climate type). Long-term (30-yr) daily mean temperatures of the region are -7.7 °C in January and 20.8 °C in July (Environment Canada, 2013a). Annual (long-term 30 year) mean precipitation is 933 mm, with 22% of the precipitation falling as snow (Environment Canada, 2013a). Snow cover is typically present between the months of November and March/April and mid-winter thaws are common.

The field site (INN1) was established in December 2010 (44°22' N, 79°35' W) and monitoring commenced in January 2011. The site has moderately sloped (1.5%, Figure 4.1), sandy loam soil from the Grey-Brown Luvisols Great Group, Bondhead and Guerin series (Hoffman et al., 1962). Soils are stony and imperfectly drained, with a clay-rich B horizon found at approximately 0.6 m depth. Tile drains (20cm in diameter) are located approximately 1 m below the soil surface, and are systematically spaced 12.2 m (40 ft) apart.

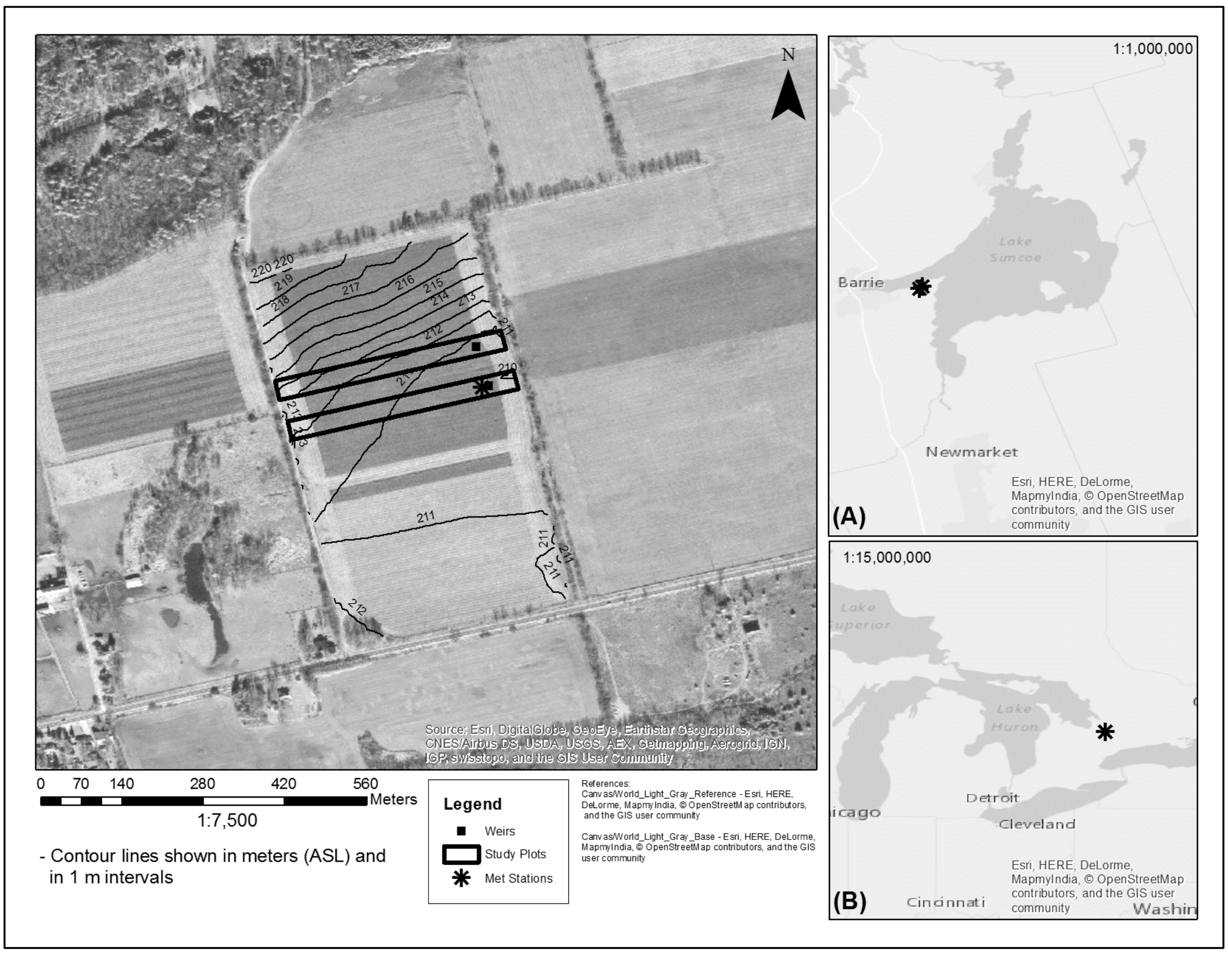

Figure 4.1: Map of the study site (INN1) and plots. The location of the site in the Lake Simcoe watershed is shown in Inset A, and in the Great Lakes region of Ontario,

Canada in Inset B. Field topography is shown in grey (contour interval 1 m). The location of the meteorological station and tile monitoring stations are shown.

The field is under corn-soybean-winter wheat rotation [Corn (2010), soybeans (2011), winter wheat (2012)], with a surface (0-15 cm) soil test P of 25 $mg \cdot kg^{-1}$ Olsen-P. The field has been under a minimum rotational till for more than 10 years (shallow 2" vertical tillage after winter wheat harvest in July/August). The field receives commercial fertilizers (190 $kg \cdot ha^{-1}$ of 14-14-11-13 NPKS fertilizer for winter wheat, applied in fall with seed, or 165 $kg \cdot ha^{-1}$ 15-10-9-15 NPKS for corn, applied in spring, 2x2 beside seed), applied in bands in the subsurface (Lam et al., 2016). No fertilizer is applied prior to soybeans. Both winter wheat and corn crops are side-dressed with nitrogen and potash (20-0-5 NPK, 350 $L \cdot ha^{-1}$ and 460 $L \cdot ha^{-1}$, respectively) in May to provide a total of approximately 120 and 150 $kg\text{-}N \cdot ha^{-1}$. Approximately 43 kg- $P_2O_5 \cdot ha^{-1}$ is applied over the entire crop rotation. Considering the potential spatial variability in soil test P levels and crop response to applied fertilizer (Kachanoski and Fairchild, 1996) this rate is above the provincially recommended P application (20 kg- $P_2O_5 \cdot ha^{-1}$) for this rotation and soil test P level (OMAFRA 2009). During the study period, P was applied in October 2011 (prior to the 2012 winter wheat crop, planted in October 2011) (Lam et al., 2016).

Within the field, two study plots (30 m wide x ~250 m length) were located above tile lines (~60 m apart). A single tile line located in the centre of each plot was monitored. The contributing area to the monitored tile line was assumed to be 50% of the distance to adjacent tiles (12.2 m), extending along the length of the entire tile line (250 m). During this period, one plot was managed under reduced tillage practices (vertical tillage following winter wheat: completed in fall 2009), and the second plot was more aggressively tilled (disk harrow, 4" depth, 1x per year). However, Lam et al., (2016) demonstrated that tillage practices did not result in differences in hydrological and biogeochemical processes (i.e. timing, speciation and magnitude of P loss) between the study plots. Consequently, data from the two plots have been pooled in the current study, and the effects of differing tillage practices are not examined in this manuscript.

4.3.2 Field Methodology

Field plots were continuously monitored from January 2011 through April 2013 inclusively. Each monitored tile was intercepted and equipped with a custom-built V-notch weir (15^{o}) and 0.5 x 0.5 m stainless steel lined box (open at the top), to allow flow and chemistry within the tile line to be accessed and monitored from the surface without impeding tile flow. An insulated metal shed was placed above the weir box to house the equipment and minimize freezing in winter. Flow (based on depth of water in the V-notch weir) was measured at 15-minute intervals using pressure transducers (Onset HOBO-U20-001-04) placed inside a stilling well within the box. Under peak flow periods, when tiles were flowing at full capacity, discharge was occasionally impeded by downstream flow and water levels rose within the riser box. Tile discharge during these periods was determined using a stage-discharge relationship developed from simultaneous direct measurements of depth, velocity and flow (Hach Flo-Tote 3 and FL900 data logger, Hach Ltd.) taken in the tile over a two-month period. This data was also used to validate discharge measurements generated by the V-notch weirs.

A meteorological station was located 30 m from the study plots within the field. The station was equipped to measure air temperature (1.0 m and 3.0 m height, Vaisala HMP45C) and rainfall (Texas Electronics TE525M) using a Campbell Scientific CR-1000 data logger at 30-minute intervals. Each study plot was equipped with soil probes at 10, 20 and 70 cm depths to measure soil temperature and moisture content (volumetric water content, VMC, Decagon Devices Inc. 5TM SM/Temp sensors with EM-50 data logger, Onset Ltd.). Installation of pre-calibrated soil moisture sensors (calibrated using soil cores extracted from the site) provided temporally relevant (collected at 15-minute intervals) volumetric soil moisture data. Estimates of snowfall were obtained from a nearby weather station located ~15 km from the study site (Station ID: 611056; Environment Canada, 2013b). Snowfall data obtained online was validated using manual snow surveys at the sites (~2 yr^{-1}).

Discrete water samples were collected for the determination of nutrient chemistry throughout the entire study period prior to, throughout and following flow events, with samples collected throughout both the rising and falling limbs of the event hydrograph. Water quality samples were collected using automated water samplers (Teleyne ISCO 6712, Lincoln, NE) equipped with actuators (ISCO 1640 liquid level actuator) to trigger sample collection when flow was detected. Sample collection was triggered for all flows when tiles were not flowing (dry), but liquid level actuators were raised (typically to ~3 cm above base of V-notch weir) during wet periods when baseflow was occurring to ensure that only events were captured. Sampling intervals were adjusted based on previous monitoring of the site and in accordance with season and the typical magnitude of events to capture the rising and falling limbs of the hydrograph. In general, samples were collected at 2-4 hr intervals during growing season, and 4-12 hr intervals in non-growing season. Water samples were retrieved from the field within 24-48 hours during the summer period, and within 2-5 days during the cooler non-growing season). Fifty-five precipitation and/or snowmelt events (>10 mm in 24 hour period) occurred over the study period. Of these, 27 generated a flow response in tile drains. An event commenced when a rise in the hydrograph was observed, and ended when the falling-limb of the hydrograph returned to pre-event flow rates (baseflow or cessation of flow) (Lam et al., 2016). Flow weighted mean concentrations (FWMC) of DRP and TP were calculated for each event using standard techniques. For each event, total tile discharge was determined from the sum of continuous flow data over the event. The loads of TP and DRP were determined by multiplying the FWMC for each event by the total mm of tile discharge for the same event (Williams et al., 2015).

4.3.3 Laboratory and Data Analyses

Upon retrieval from the field, a 100 mL aliquot taken from each sample was immediately passed through a 0.45 μm cellulose acetate filter and refrigerated for the analysis of dissolved reactive phosphorus (DRP). A second 100 mL unfiltered subsample was preserved with acid (to achieve a final concentration of 0.2% sulfuric acid) for the analysis of total phosphorus (TP). Phosphorus contents in water samples were analyzed using standard colorimeteric methods (Bran-Luebbe AutoAnalyzer III system, Seal Analytical, Methods G-103-93 (DRP, detection limit

0.001 mg·L^{-1}-P), G-188-097 (TP, detection limit 0.01 mg·L^{-1}-P) in the Biogeochemistry Lab at the University of Waterloo.

To better understand the relationship between discharge and P concentrations and P loads, linear regression analysis was used. Prior to statistical testing, data were tested for serial dependence and temporal autocorrelation (Helsel and Hirsch, 2002). Where autocorrelation was found, it was removed through the removal of redundant data points. In general, this was done with the use of averages where redundant data points existed. Linear regression tests were done on both instantaneous data (instantaneous flow and DRP or TP concentrations), and for event-based data (total mm tile discharge per event and FWMC or loads for DRP and TP). To examine seasonal and inter-annual differences in P concentration and load, linear regression tests were done for all data (pooled) as well as for individual years (2011, 2012, 2013) or seasons (winter [JFM], spring [AMJ], summer [JAS] and fall [OND]). To examine seasonal differences in soil moisture content, a non-parametric one-way Analysis of Variance (ANOVA) was used, as the data set did not meet the assumption of normality. To examine relationships between antecedent soil moisture content and runoff ratios for events, a Spearman's Rho test was used. To assess the predictive power of our simple precipitation-P load model, the Nash–Sutcliffe model efficiency coefficient was used. Relationships were accepted as significant where $p<0.05$. All statistical tests were done using SPSS (v.22).

4.4 Results and Discussion

4.4.1 Temporal variability in meteorological conditions, discharge and phosphorus concentrations

Conditions in 2011 (945 mm precipitation, 17% as snow; 6.7 °C mean air temperature) and 2013 (933 mm precipitation, 22% as snow; 6.0 °C mean air temperature) (Figure 4.2) were consistent with 30-year long-term climate normals for the region (933 mm precipitation, 24% as snow; 6.9 °C mean air temperature, Environment Canada, 2013a). However, 2012 experienced an anomalously warmer winter (-0.6 °C mean air temperature, 5.2 °C above the climate normal of -5.8 °C in January through March (Environment Canada, 2013a), a mean annual air temperature of 7.8 °C), and low precipitation throughout most of the year (748 mm, 15% as snow, 206 mm below average).

The majority of the precipitation deficit experienced in 2012 occurred in the earlier portion of the year (January through July, inclusive; 299 mm, compared to long term normal of 509 mm over this period, Environment Canada, 2013a, Figure 4.2) whereas the period of August through December was more typical of long-term norm (Environment Canada, 2013a).

These differences in precipitation among the years are reflected in discharge volumes in tile drains (Figure 4.2), where markedly less discharge was observed in 2012. This is reflected in the differences in annual runoff ratios (the ratio of tile discharge to precipitation received for a given event); 2011 (0.24), 2012 (0.15), 2013 (0.25 from January through June, inclusive) (Lam et al., 2016). The runoff ratios observed at this site were lower than what was observed in 2012 from clay loam and silt loam soils in Ontario (35-55%, Van Esbroeck et al., 2016), and lower than what has been reported by other studies (~40%, Macrae et al., 2007a; King et al., 2015a). Runoff ratios in the current study also did not differ between the two plots (one tilled, one with rotational, conservation till) (Lam et al., 2016), which is in contrast to what has been reported by others, where no-till practices have been shown to enhance runoff in tile drainage (King et al., 2015a).

Soil temperatures reflected air temperatures (although soil temperature fluctuations were dampened), with the exception of the winter months when snow cover was present. Soil temperatures remained slightly above freezing during all three winter periods (Figure 4.2), demonstrating the role of the snowpack in insulating soils. This has implications for the generation of surface runoff, as frozen ground has been shown to impede infiltration in winter in other regions (e.g. Shanley and Chalmers, 1999; McCauley et al., 2002; Cade-Menun et al., 2013) The presence of a snowpack (~16 mm SWE, long-term average for January in this region) may minimize frost extent in soils, permitting the infiltration of meltwater, and permitting tile drains to flow during warming events. The year-round connection between tiles and the surface following events is reflected in both changes in soil moisture content (VMC) and tile discharge that were observed following both rainfall events and winter thaws/snowmelt (Figure 4.2). Soil moisture also demonstrated both seasonal and inter-annual variability, where soil moisture contents were lowest during the summer periods of 2011 and 2012 (especially during the drought in 2012) but similar at other times of year (Figure 4.2).

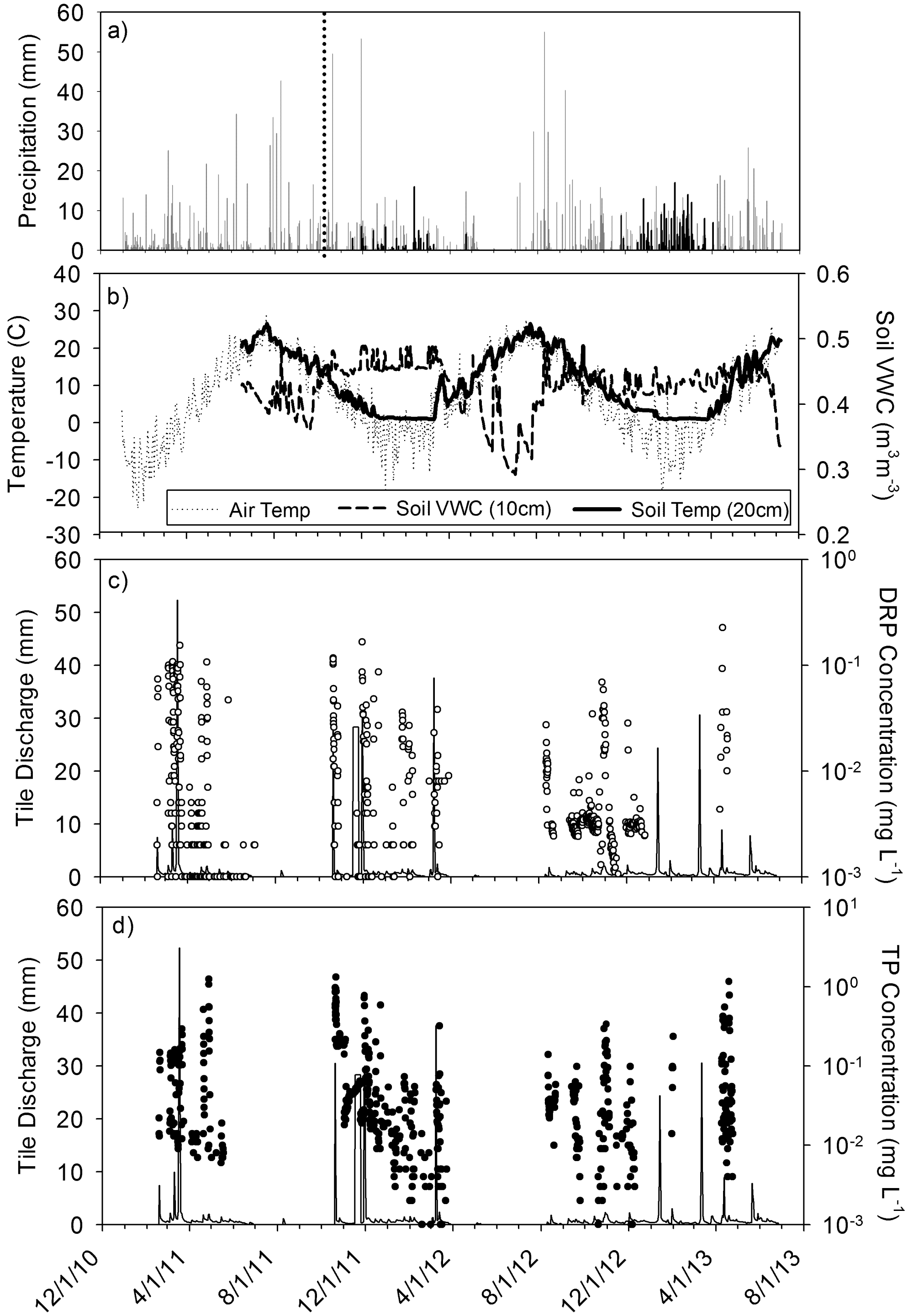

Figure 4.2: Meteorological conditions and tile drain hydrologic and biogeochemical responses recorded over the study period. (a) Precipitation (snow is shown in black and total precipitation (rain + snow) is shown in grey). Only bulk precipitation data are available prior to Fall 2012, denoted by dotted line); (b) Air and soil (10 cm) temperature, and soil moisture (10m); and, Tile discharge (line) and instantaneous concentrations (symbols) of (c) DRP and (d) TP.

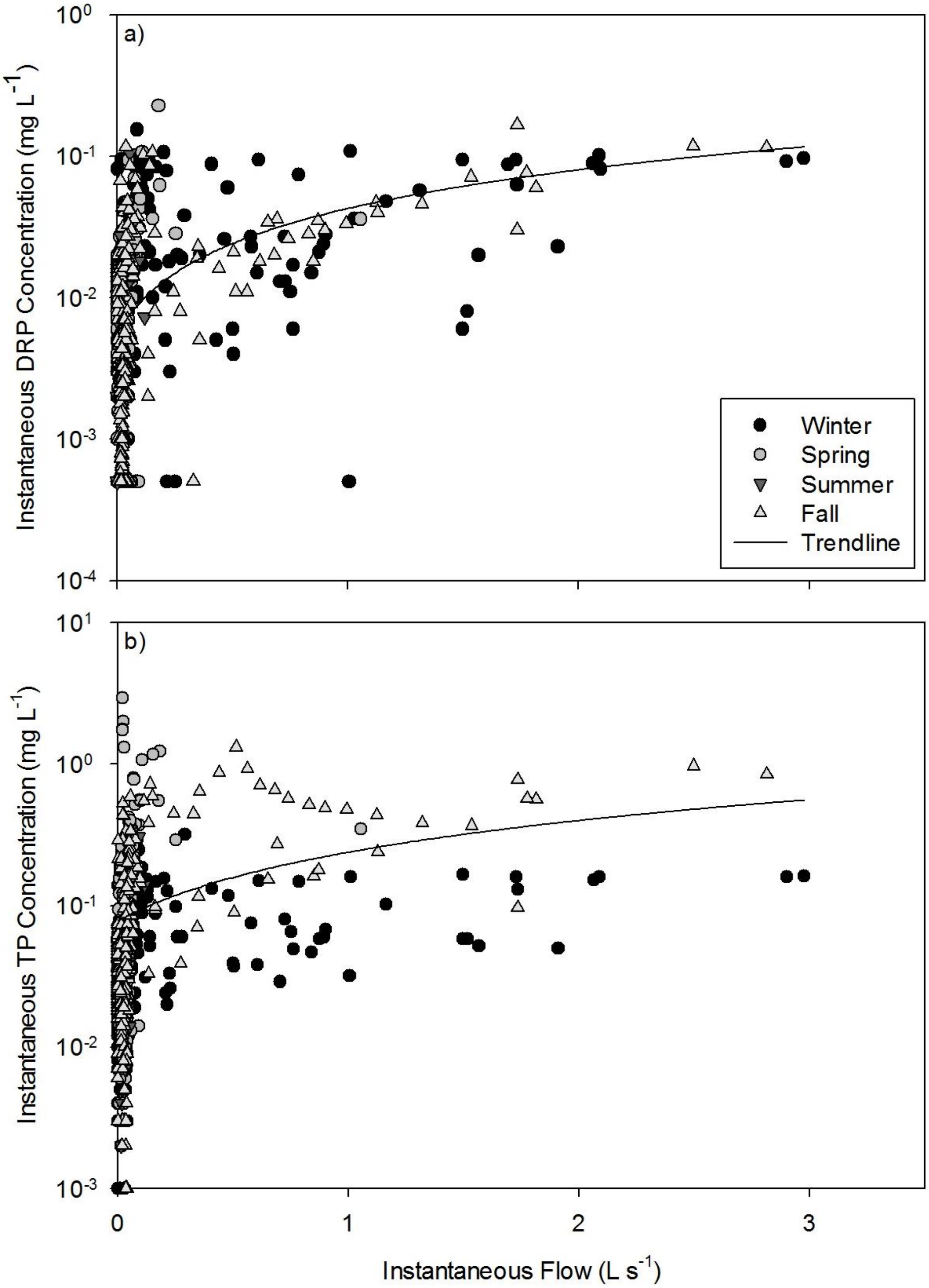

Figure 4.3: Scatterplot of instantaneous tile discharge (recorded at 15 minute intervals) and DRP (a) and (TP) concentrations. The winter (JFM, black circles), spring (AMJ, grey circles), summer (JAS, black triangles) and fall (OND, grey triangles) seasons are differentiated in the figures. The trendline shown is fitted to all of the data (pooled).

Runoff generation in tile drains corresponded with rainfall and snowmelt events, although these responses were generally restricted to the non-growing season and were rarely observed in summer. Tile discharge was highly episodic (Figure 4.2), and 27 discrete discharge events were recorded over the study period (spanning 143 days over 852 days of total study period, or 17% of the time). Although baseflow was observed between storm events in fall and spring, and also between many events occurring in winter, tiles generally did not flow during the summer months and baseflow did not occur in tile lines (i.e. tiles were dry). The episodic nature of runoff responses has been observed by others, where a substantial volume of annual runoff is observed during the NGS (Jamieson et al., 2003; Macrae et al., 2007a; Hirt et al., 2011; King et al., 2016; Lam et al., 2016; Van Esbroeck et al., 2016). Studies have shown that tile drains rapidly respond to precipitation inputs (e.g., Gentry et al., 2007; Smith et al., 2015b), although hydrologic responses may vary with both antecedent moisture conditions and precipitation intensity (Macrae et al., 2007a; Vidon and Cuadra, 2011).

Increases in DRP and TP concentrations were observed during discharge peaks, and varied throughout events. Given that the majority of flow occurred during the non-growing season, the majority of P loading in tile drains was also observed between October and April, when P export exceeded 98% of the annual amount (Figure 4.2, and Lam et al., 2016). In general, P concentrations and loads from this site were low (104 g DRP ha^{-1}, 464 g TP ha^{-1}) in 2011 and 9 g DRP ha^{-1}, 48 g TP ha^{-1} in 2012, Lam et al., 2016) compared to what has been observed in other studies (e.g. Sims et al., 1998; Gentry et al., 2007; Macrae et al., 2007a; Vidon and

Cuadra, 2011; Smith et al., 2015b), particularly sites with clay soil. The small loads in the current study are likely due to a combination of low runoff volumes (given the smaller runoff ratios observed at this site in comparison to other studies, discussed earlier), and, smaller P concentrations in runoff, which are likely a result of management practices used at the site (nutrient management, rotational conservation tillage, subsurface P placement, Lam et al., 2016).

4.4.2 Relationships between Discharge and Phosphorus Dynamics

Instantaneous DRP and TP concentrations collected during the study period were temporally variable both within and among events, and with respect to discharge magnitude and across seasons and years (Figure 4.2). Relationships were not found between tile discharge and concentrations of DRP or TP (all data pooled, Figure 4.3).

Additional regression analyses between instantaneous flow and P concentrations were conducted on data separated by year or season to explore inter-annual or seasonal variability; however, this did not improve the strength of the statistical relationships [$p>0.05$; $R^2<0.04$] with the exception of summer DRP concentrations, which showed a positive relationship with instantaneous flow [$F=11.75$; $p=0.04$; $R^2=0.80$], although the relationship was strongly influenced by one high data point. Flow-weighted mean concentrations (FWMC) of DRP and TP were subsequently examined as a function of event magnitude (Figure 4.4).

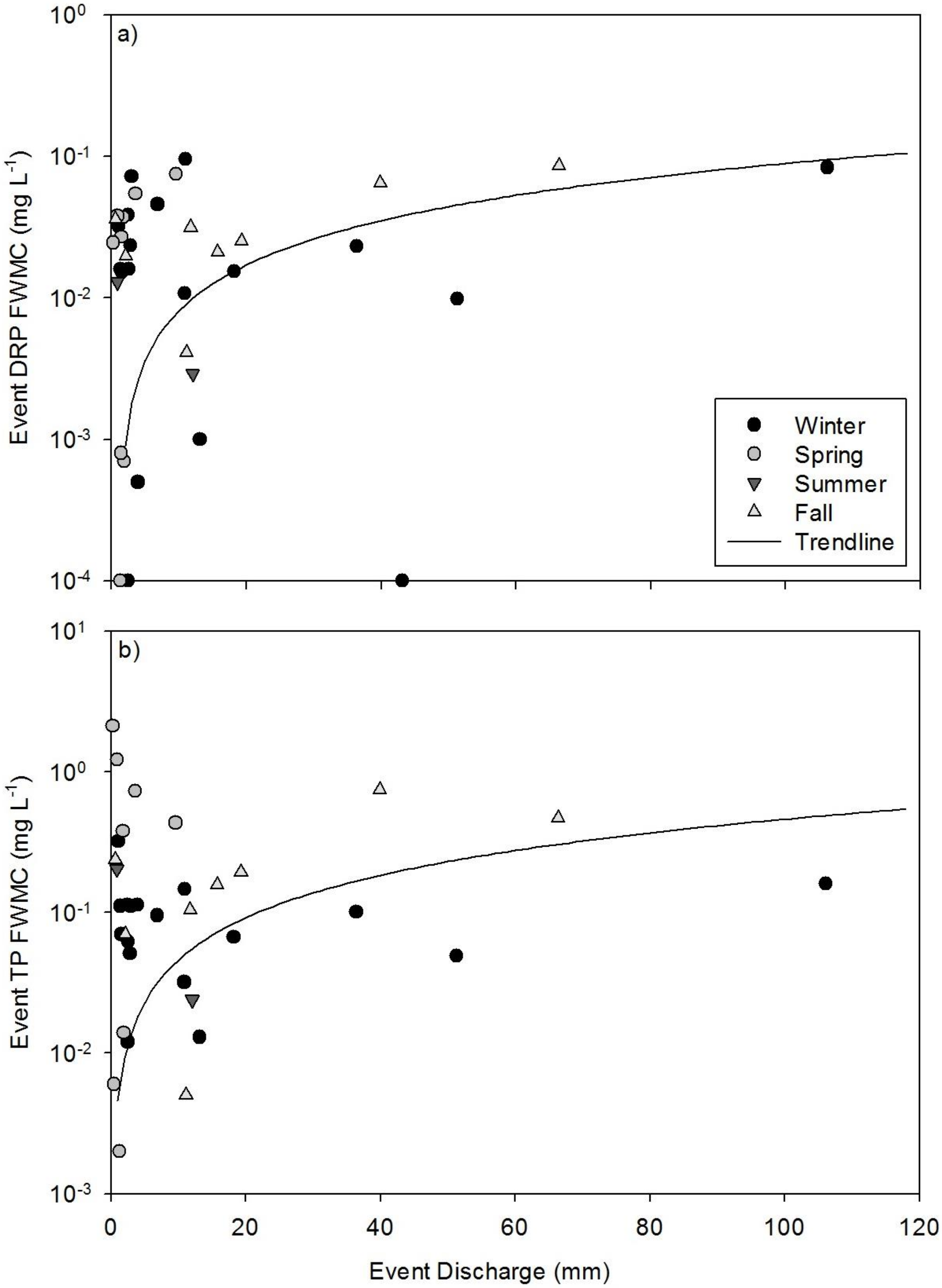

Figure 4.4: Scatterplot of tile discharge and flow-weighted DRP (a) and (TP) concentrations for individual events captured over the study period. The winter (JFM, black circles), spring (AMJ, grey circles), summer (JAS, black triangles) and fall (OND, grey triangles) seasons are differentiated in the figures. The trendline shown is fitted to all of the data (pooled).

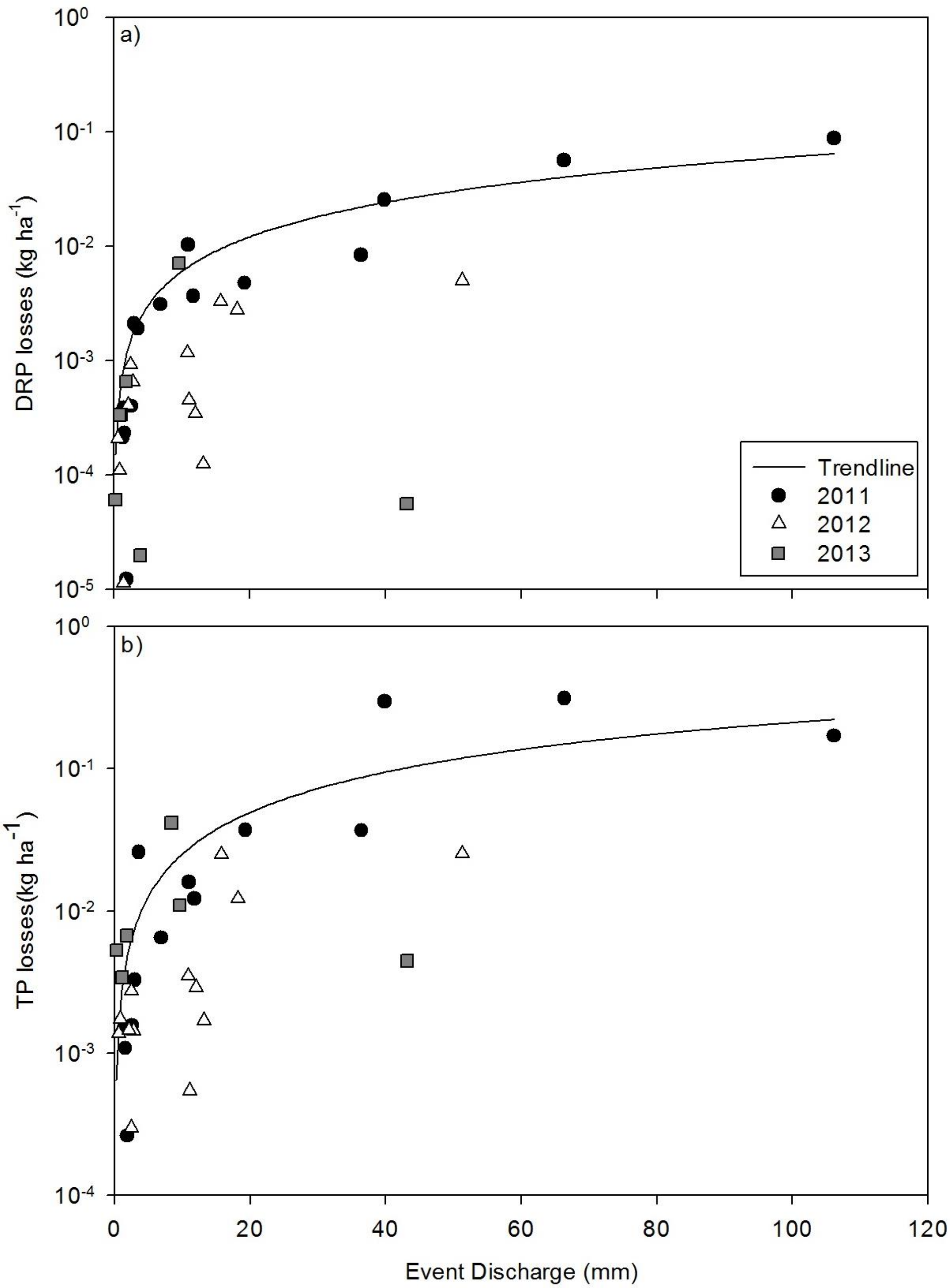

Figure 4.5: Scatterplot of instantaneous tile discharge and DRP (a) and (TP) loads for individual events recorded over the study period. The three study years (2011, 2012 and the early portion of 2013) are differentiated in the figure. The trendline shown is fitted to all of the data (pooled).

As was done for instantaneous data, events were examined both pooled and as a function of season and year. Across the entire data, we found a weak but significant relationship between discharge and FWMC-DRP [$F=7.178$, $p=0.011$, $R^2=0.16$] and FWMC-TP in Fall [$F=6.64$, $p=0.04$, $R^2=0.53$], but no other significant relationships. Thus, discharge data is not a good metric for the prediction of P concentrations in tile drain effluent at our site. This is consistent with what has been shown by others at the watershed scale (e.g. Beauchemin et al., 1998; Gentry et al., 2007; Macrae et al., 2007a, King et al., 2015a), where less is known about tile drainage (Macrae et al., 2007a; Smith et al., 2015b; King et al., 2015a; Sharpley et al., 2015).

An examination of event magnitude (mm) and P load ($kg \cdot ha^{-1}$) (Figure 4.5) yielded better relationships for both DRP [$F=119.51$, $p<0.001$; $R^2=0.76$] and TP [$F=27.33$, $p<0.001$; $R^2=0.49$], suggesting that despite the poor discharge-concentration relationships observed in Figures 4.3 and 4.4, P loss by mass as a function of event size and P loss for a given event can be predicted reasonably well if discharge is monitored. This supports the findings of other studies that have also observed this (e.g. Macrae et al., 2007b; Basu et al., 2010). Significant relationships [$p<0.05$] were found between tile discharge and DRP and TP loads for 2011 and 2012, as well as for spring and winter (for DRP) and fall and winter (for TP) (Figure 4.5).

Although relationships between discharge and P loads for captured events were found across the pooled data, subtle differences were observed among the study years where P concentrations were lower in the very dry year of 2012 in comparison to 2011 and 2013 (Figure 4.5). Given that fertilizer was applied in

October 2011, it was expected that P concentrations would be elevated over the period immediately following fertilization in fall 2011 and spring 2012. Thus, our results are in contrast to what has been observed by others, where loads are higher following P application (Djodjic et al., 2000; Heathwaite and Dils, 2000; Gentry et al., 2007; van Esbroeck et al., 2016). The reasons behind the smaller loads under similar magnitude events in 2012 compared to the other two years are unclear, but may have been related to the fact that 2012 was an exceptionally dry year. The fact that elevated P loads were not observed following the application of P fertilizer may also have been related to the fact that P is added via banding in the subsurface at the study site. Indeed many incidences of elevated P loss following P fertilizer application have been observed following surface broadcasting of P fertilizers, particularly on no-till soil (e.g. Sharpley and Smith 1994; Tiessen et al. 2009; Kleinman et al., 2015b).

Our findings suggest that capturing variability in discharge volume may be more important than capturing variability in P concentrations throughout a given event when attempting to generate estimates of P loading from tile drains within a site. This has been shown in watershed scale studies (Beauchemin et al., 1998; Gentry et al., 2007; Macrae et al., 2007a, King et al., 2015a), but fewer studies have explored such relationships in tile drainage (Macrae et al., 2007a; Williams et al., 2015). This has significance for monitoring programs where managers are often faced with significant budgetary constraints and must make decisions related to sampling frequency. The fact that P loss in drainage tiles can be reasonably predicted from tile discharge at some sites (such as the site in the current study) is promising as it may allow managers to make general predictions of subsurface P loading from a field or suite of fields if flow can be directly measured or modeled. Although P loads may be predicted using discharge after several years of baseline data have been collected, it is important to continue to collect water samples to most accurately calculate loads (Williams et al., 2015).

Although models have been created for the prediction of P loss in tile drainage (Radcliffe et al., 2015), many of these models do not adequately account for the complex nature of P transfer in tile drainage (Kleinman et al., 2015a). Previous studies have demonstrated poor relationships between discharge and P concentrations in tile drain effluent (Macrae et al., 2007a; King et al., 2015b). Some of this variability has been attributed to the presence of preferential pathways and pipe flow (cracks) that rapidly route surface runoff into tile drains (Sims et al., 1998; Stamm et al., 1998; Goehring et al., 2001) and the fact that such preferential connectivity is typically found on the rising limb of the hydrograph (Djodjic et al., 2000; Heathwaite and Dils, 2000). However, preferential transport can occur via different types of pathways including biopores and cracks, but the biogeochemical contribution of these pathways can vary considerably in space and time (Kleinman et al., 2009; Reid et al., 2012). Much of the previous work on P loss in tile drain effluent has been conducted in clay soils where vertical cracking is prevalent (e.g. Stamm et al., 1998, Kleinman et al., 2015b) and it is unclear to what extent, if at all, this can be extended to medium and coarser textured soils.

4.4.3 Can discharge and phosphorus loss in tile drains be predicted from simple hydrometric measurements?

An examination of instantaneous soil VMC and runoff in the drainage tile (Figure 4.6a) demonstrates clear thresholds above which flow is observed, and below which very little or no flow is observed. Data are shown for one plot and one tile in Figure 4.6, but the same patterns were observed for both plots. The thresholds were determined visually (Figure 6a; ~0.49 $m^3 \cdot m^{-3}$ volumetric soil moisture content in the top 10 cm, ~0.47 $m^3 \cdot m^{-3}$ at 20 cm depth, and ~0.36 $m^3 \cdot m^{-3}$ at 70 cm depth) and correspond with conditions that are at or close to saturation for our sandy loam soil, and exceed the field capacity (~0.45 $m^3 \cdot m^{-3}$ for the top 10-20 cm of soil, ~0.32 $m^3 \cdot m^{-3}$ at 60 cm depth, determined using soil cores in the laboratory). The threshold within a given soil horizon did not change with precipitation intensity, or between rainfall and snowmelt events (Figure 4.6a). An examination of the seasonal distribution of VMC content in the top 10 cm of soil (Figure 4.6b) demonstrates that during the fall and winter months (and occasionally in spring), soils are at or near field capacity (or above it when tiles are flowing), whereas in spring (particularly late spring) and summer, they are frequently beneath this. A one-way ANOVA test examining differences in VMC with season (winter, spring, summer, fall) yielded significant differences [$F=234.22$, $p<0.001$]. Post-hoc analyses (Mann-Whitney U) revealed that differences were significant among all seasons ($p<0.001$) with the exception of fall and winter ($p=0.471$). Minute quantities of discharge were observed in both drainage tiles at moisture contents below this threshold (< 0.2 $L \cdot s^{-1}$ L/s), likely attributed to preferential flow via macropores following rainfall in summer (Tan et al., 1998; Jarvis, 2007; Kleinman et al., 2009; Reid et al., 2012).

However, such small volumes were insignificant when compared to losses throughout the remainder of the events that they contributed to, or, events occurring throughout the year. Our data demonstrate that antecedent moisture conditions in soil between October and April are frequently conducive to the generation of substantial discharge in tile drains, if a precipitation or thaw event occurs.

Indeed, runoff ratios (discharge:precipitation) for non-growing season events (0.75) are greater than during the growing season (0.20) (Macrae et al., 2010; Lam et al., 2016). Soil moisture at field capacity with small soil storage potential will result in tile discharge being triggered by smaller precipitation and snowmelt inputs during the non-growing season (Figure 4.2, 4.6). For discharge to occur between April and September, when evapotranspiration rates are high, a larger precipitation input is required to satisfy the greater soil-water storage potential. This is consistent with other studies that have observed greater runoff ratios with wetter antecedent soil moisture conditions (Wei et al., 2007; Brocca et al., 2009; Radatz et al., 2013). Previous studies have linked antecedent soil moisture and runoff responses (Pauwels et al., 2001; Scipal et al., 2005; Zehe et al., 2005; Wei et al., 2007; Brocca et al., 2009; Macrae et al., 2010; Radatz et al., 2013), but this has largely been shown for surface runoff or watershed scale runoff and has not been shown for subsurface runoff in drainage tiles.

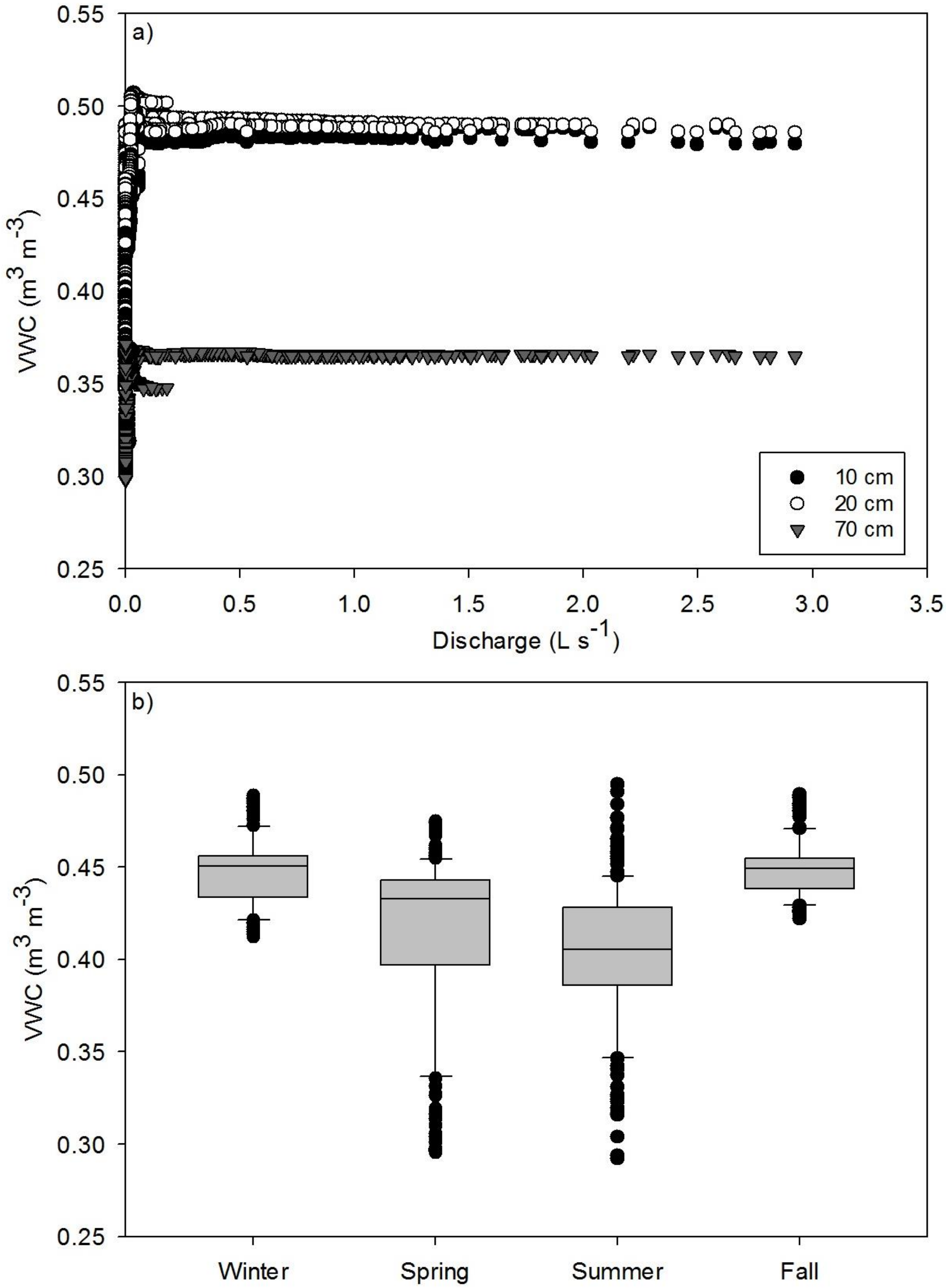

Figure 4.6: (a) Relationship between tile discharge and soil volumetric moisture content at 10 cm (black circles), 20 cm (white circles) and 60 cm (grey triangles) depth. Data were recorded at 15 minute intervals; (b) Boxplots showing the seasonal distribution of soil volumetric moisture content in the top 10 cm of soil. Boxes represent the 25th, 50th and 75th percentiles and whiskers represent the 10th and 90th percentiles. Circles represent outliers.

Previous work on the generation of runoff in drainage tiles has demonstrated that hydrologic connectivity between tile drains and surface soils in loam soils increases with soil moisture content, as field capacity is reached and surpassed (Kung et al., 2000a, 2000b; Macrae et al., 2010), and, the lack of tile drainage in summer has been attributed to rainfall replenishing a soil storage deficit (Macrae et al., 2007a). Indeed, runoff ratios for our sampled events were positively correlated with antecedent soil moisture content prior to the event (Spearman's Rho = 0.461, p=0.014, not shown). Although others have examined relationships between antecedent soil moisture content and tile discharge (e.g. Vidon and Cuadra, 2011), to our knowledge, the clear thresholds in soil moisture content and tile discharge demonstrated in the current study have not been shown previously.

In a parallel study at the same site, Lam et al. (2016) demonstrated that hydrologic and biogeochemical responses in tile drains were not affected by tillage practices. This differs from the scientific literature on studies conducted in heavier textured soils where no-till management practices have been shown to enhance preferential pathways between the soil surface and tile drains (Cameira et al., 2003; Jarvis, 2007; Ulén, 2010). Both plots at the site demonstrated the same threshold behavior for hydrologic storage, soil VMC and runoff generation in tile drains, suggesting that medium and coarser textured soils may not be at as much risk for the rapid transport of P into tiles under unsaturated conditions that has been observed by others in clay soils (e.g. Sims et al., 1998; Gentry et al., 2007; Reid et al., 2012; King et al., 2015a). However, the risk of preferential transport of P into tile drains under saturated conditions may still be high. Klaus et al. (2013)

demonstrated that macropore flow was not initiated until soil layers near the soil surface became saturated. Under saturated conditions it is likely that the surface soil and tile drains become hydrologically connected allowing for the rapid transport of P from surface layers into tiles. Despite this potential, the two plots at the current study site did not differ in their rates of P loss through tile drains, even under saturated conditions (Lam et al., 2016).

The effects of precipitation amount on tile drainage responses across seasons are shown for the 55 precipitation events that occurred over the study period (Figure 4.7a). We considered only those rainfall events exceeding 10 mm within a 24-hour period, or any loss via snowmelt. Of the 55-precipitation/snowmelt events documented, 27 produced runoff in tile drains. Low volume precipitation events frequently did not produce a runoff response, further demonstrating the need for precipitation inputs to pass a threshold storage volume before discharge will occur in tile drains. An examination of the seasonal distribution of discharge responses to precipitation demonstrates that events that did not result in a runoff response were most frequently observed during the summer months (Figure 4.7a), coincident with the lower VMC observed during this period (Figure 4.6b), which likely resulted from greater rates of evapotranspiration in comparison to other times of year. In contrast, most winter events fell fairly close to the 1:1 line comparing precipitation and discharge (i.e. runoff ratios approaching 1). This is likely attributed to smaller evapotranspiration rates, and a lower soil storage capacity during winter events when soils consistently have greater soil moisture contents derived from fall wetting and mid-winter thaw events (Figures 4.6b, 4.7a). To further examine the relationship between precipitation inputs, antecedent moisture conditions and tile drain runoff response, the discharge for a given event was plotted as a function of precipitation (Figure 4.7b), but only for precipitation received after the soil VMC reached the threshold observed in Figure 6a. We hypothesized that under nearly saturated soil conditions or at least field capacity, the amount of additional precipitation input would directly correlate with the magnitude of tile drainage. Indeed, once the VMC threshold was reached, more data points fell along the 1:1 line in the precipitation:discharge plot (Figure 4.7b), although this was not always the case. Events that deviated from the 1:1 line were summer or autumn events, and it is possible that soil above 10 cm was significantly drier and had greater storage potential, reducing the runoff ratio. Indeed, such drying could have resulted from the very dry summer seasons but may also have been related to tillage at the sites. The site was tilled in August 2012, after the harvest of winter wheat, which can temporarily increase the storage capacity of the upper soil layer. Given the very low-disturbance tillage done at the sites, the dry conditions are a more plausible explanation. There were several events that also fell above the 1:1 line in Figure 4.7b, the majority of which were winter events.This may be the result of heterogeneity in snow-water equivalency that was not accounted for, or lateral flow along the slope found at the site, or small errors in the delineation of individual events. When soils are at field capacity, they are holding as much moisture as possible after excess water has drained due to gravity (Milly, 1994; McNarmara et al., 2005; Wang and Alimohammadi, 2012).

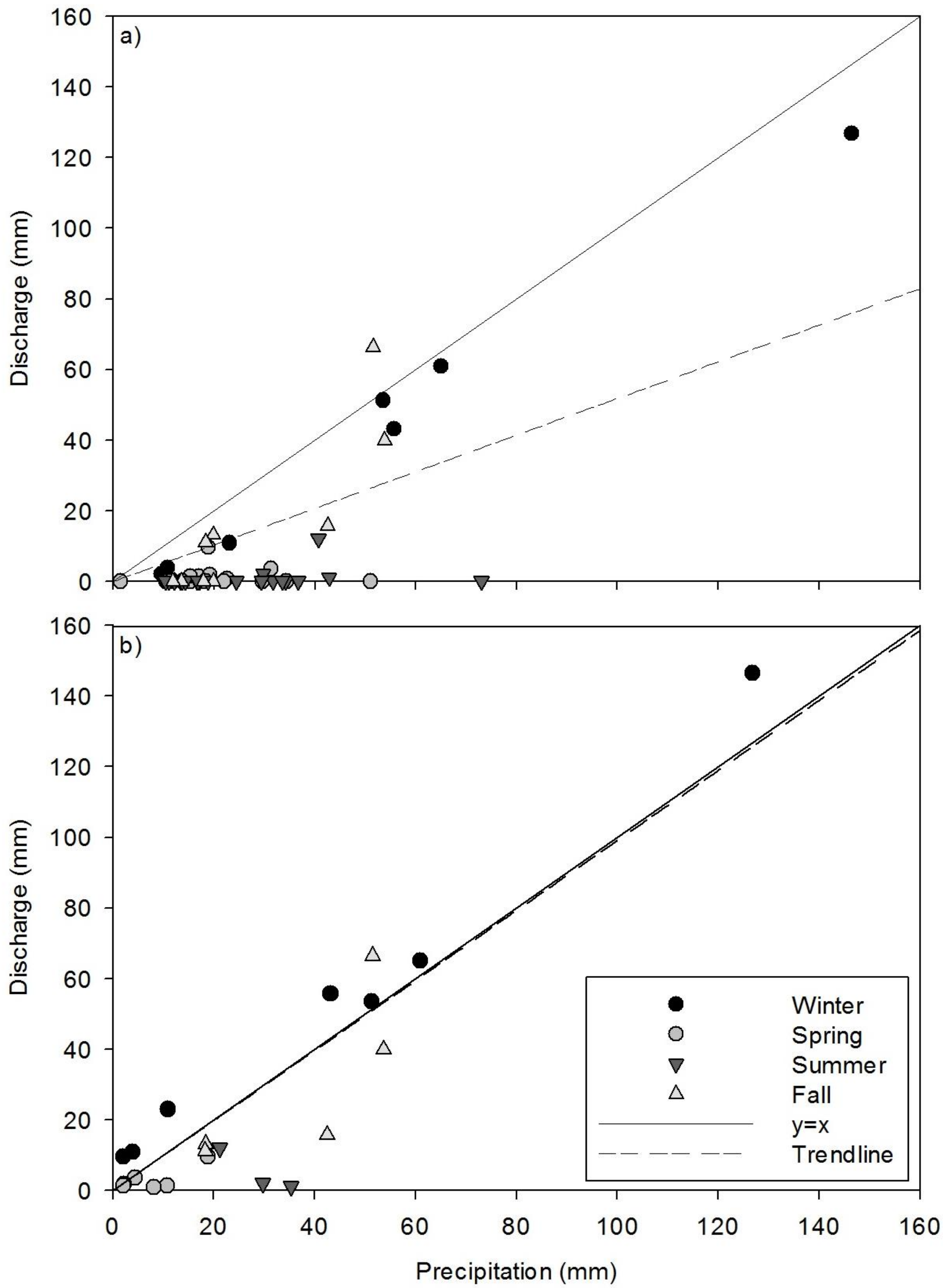

Figure 4.7: (a) Relationship between precipitation and tile discharge for individual events recorded over the study period; and (b) for precipitation contributing to an event after the soil volumetric content reached the threshold moisture content shown in Figure 4.6 (0.49 m^3 m^{-3} in the top 10 cm). The winter (JFM, black circles), spring (AMJ, grey circles), summer (JAS, black triangles) and fall (OND, grey triangles) seasons are differentiated in the figures. The trendline shown (dashed line) is fitted to all of the data (pooled). The 1:1 line (solid line) is also shown.

Consequently, any additional hydrologic inputs to the system should freely drain rather than being held in the soil profile. It is assumed that water from precipitation events that did not trigger runoff in tile drains simply replenished soil storage. Other studies have also found that runoff coefficient are significantly higher in storms with high antecedent soil moisture (Wei et al., 2007; Brocca et al., 2009; Radatz et al., 2013), and differences in year-to-year discharge can be explained by differing soil moisture conditions (Scipal et al., 2005), which could be used to predict discharge (Brocca et al., 2009). This is consistent with the work of Berkowitz and Ewing (1998) who demonstrated that soils retain water below a threshold soil moisture, and until this threshold is surpassed, hydraulic conductivity is zero in the unsaturated zone. A percolation threshold is achieved when soil particles no longer retain water and pathways are created through the matrix (flow activation). Although it was evident that there was soil water percolating through the soil profile before flow in the drainage tiles was triggered (as changes in soil moisture content were observed, Figure 4.2), runoff generation in drainage tiles did not commence until the soil moisture threshold was reached. This threshold coincides with the inflection point on the tile hydrograph, where a steep rise is observed (Figure 4.2, and Katz and Thompson, 1986; Berkowitz and Ewing, 1998). The relationships generated here demonstrate that the hydrologic responses of tile drains can be predicted from easily monitored variables such as precipitation inputs (rain or melt) and a metric for soil moisture storage (such as VMC).

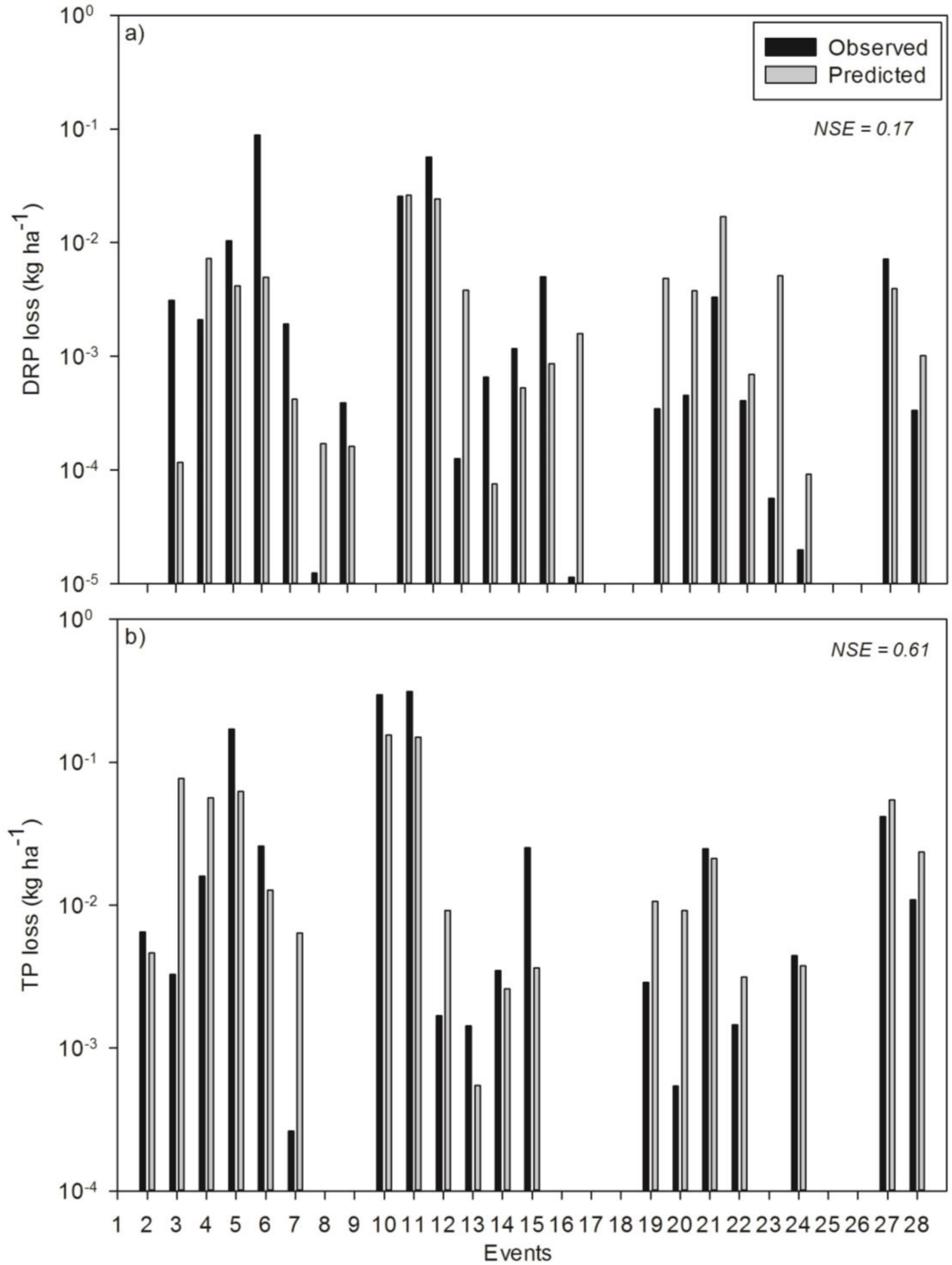

Figure 4.8: DRP (a) and (TP) loads predicted from precipitation received after soil reached the threshold moisture content shown in Figure 4.6 (0.49 m^3 m^{-3} in the top 10 cm). Observed (black) and predicted (grey) are shown for all events captured over the study period. The Nash-Sutcliffe efficiency coefficient (NSE) for DRP and TP are included in the figure panels.

This information may be useful in modeling efforts such as DRAINMOD (Singh et al., 1994; Skaggs et al., 2012), KINEROS2/AGWA (Goodrich et al., 2012), HYDRUS2D (Simunek et al., 1999; McNamara et al., 2005) and EPIC/APEX (Wang et al., 2012b).

As a final exercise, we hypothesized that if a strong relationship could be found between (a) precipitation inputs and runoff response in tile drains (Figure 4.7), and, (b) runoff in tile drains and P loss (Figure 4.5), these relationships could be combined to estimate P loss in tile drains from estimates of precipitation inputs (Figure 4.8). A comparison of the observed and modeled data for our suite of events yielded Nash-Sutcliffe efficiency coefficients of 0.17 for DRP and 0.61 for TP. Thus, our ability to predict TP loss in tile drainage using this simple model is better than our ability to predict DRP loss. Although these estimates are site-specific and may change with soil texture, crop type and rotation, and soil P content, the demonstration that simple relationships like these can be found is useful for site managers wishing to estimate watershed loads, and, is also useful in the development of simple models.

4.5 Conclusion

Precipitation inputs and antecedent soil moisture conditions are the primary factors driving runoff generation in tile drains in sandy loam soils. In addition, tile runoff magnitude appears to be the best predictor of P loads in tile drains. In the absence of direct measurements of flow, precipitation amount for a given event provides a crude surrogate for tile runoff response and P loads. This research suggests that it is possible to crudely predict hydrological and nutrient responses using easily measured, simple hydrometric parameters, once baseline conditions at the site can be established, although nutrient load estimates will be subject to uncertainty if water samples are not collected to confirm loads. This information may assist site managers and the modeling community. Our research also suggests that the hydrologic and biogeochemical responses of tile drains in coarser textured soils may differ from what has been shown for heavy clay soils. Direct field comparisons of tile hydrologic and biogeochemical responses between sites with differing soil textures but comparable management practices are needed to test this.

Chapter 5 – Major Conclusions of Thesis

Tile drains have been identified as a source of P. Much of the existing literature focused on agricultural clay soils with heavy soil textures that are prone to cracking and shrinking (Bouma, 1981; Djodjic et al., 2000; Macrae et al., 2007a; King et al., 2015b), this research has explored the effects of tile drainage and tillage method on sandy loams found in southern Ontario and its implications on tile drainage and P-export.

Phosphorus losses from the research site were lower in concentration and mass compared to other studies (e.g. Sims et al., 1998; Gentry et al., 2007; Macrae et al., 2007a; Vidon and Cuadra, 2011; Smith et al., 2015a, 2015b). The sandy loams at the site did not form cracks when dry like those of clay soils (Reid et al., 2012; Smith et al., 2015b), and therefore the site did not experience preferential drainage under unsaturated conditions in the summer or other dry periods found in other drainage tile studies. Instead, precipitation falling on unsaturated conditions did not produce flow and went into storage. In loam soils, macropores are more active under wet conditions (Kung et al., 2000a, 2000b). Indeed, higher P loss was observed in tiles under wet conditions.

In contrast to what other studies have found (Rahm and Huffman, 1984; Djodjic et al., 2005; Ulén, 2010), the results of this research show that in the sandy loam soils studied, the tillage method used by the farmer did not change the amount of P or drainage effluent exported via drainage tiles. The lack of tillage may have increased macropore density, but this did not appear to affect P loss in tiles. This may be the result of existing the nutrient management and fertilizer application strategies employed at the site.

Other differences in runoff or P-loss traditionally thought to result from different tillage practices such as increased PP losses in conventional tilled soils (Djodjic et al., 2005; Ulén, 2010) or higher DRP concentrations due to P-stratification and macropores in reduced tillage systems (Michalak et al., 2013; Kleinman et al., 2015a), were not observed at the research sites during the study period. Tile drains in coarser textured soils such as the sandy loams studied may have less potential to export P in comparison to more heavily textured/clay soils because of their hydrological properties. Thus, reduced tillage may be a viable BMP in loams. Based on the collected data, the current management system, in conjunction with the combination of BMPs employed, is likely an effective method of reducing P loss in tile drainage at this site.

Manuscript one showed that differences in P-export between the two fields (INN1, INN2) were due to soil test-P variability as the low soil test-P of INN2 (5 mg/kg) produced much less P export throughout the entire length of the study compared to INN1 (25 mg/kg). Soil test-P concentrations has been linked to the concentrations of P in runoff in other studies (Sharpley et al., 2001; Wang et al., 2012a). Therefore, maintaining low soil test P levels may be a very efficient BMP for reducing P loss from agricultural fields.

Differences seen between plots (i.e. the RT and AT treatments) on the INN1 field were due to topography at the site, as tiles in the topographic depression exported more effluent and P. This is apparent from the differences observed during the baseline period (January 2011 to August 2012) when all plots had the same RT treatment. The results of the baseline period and post-treatment period show the importance of baseline data, even in "paired" studies, as natural spatial variability can exist even within a single field, let alone adjacent fields.

The lack of differences in runoff or P loss among the plots may be a result of site-specific factors (e.g. climate, soil type), and, may also be a result of the P management strategies employed at the sites (nutrient management, subsurface placement, reduced tillage). The work produced in this thesis suggests that in areas with similar climates and soil types as the study sites (i.e. cool, temperate climates and sandy loam soils), soil tillage may not have direct implications on P loss when several nutrient BMPs are employed.

Flow via drainage tiles was episodic and followed seasonal trends, much of the annual hydrological losses and P-export occurred over a small number of days and the majority of tile-export took place during the non-growing season between November and April, which is similar to the hydrologic characteristics found in other studies (Gentry et al., 2007; Macrae et al., 2007a; King et al., 2014; Smith et al., 2015a). Inter-annual variability in tile flow and P-loss was significant. The low precipitation input of 2012 significantly reduced the amount of effluent that moved through the tile drains, but the general seasonal pattern was typical of what is observed in the region (e.g. Macrae et al., 2007a). This research shows the importance of year round monitoring due to the short-lived nature of event flows and the importance of events during the non-growing season and snowmelt. Manuscript one highlighted the importance of understanding winter processes as well as the importance of BMPs to be effective during and following frozen periods. BMPs and future research should be aware that the majority of annual tile drain losses of P occurs in a small number of days, which has implications on the timing of fertilizer application. Other studies have shown that runoff events post fertilizer application prompt larger P-export (Djodjic et al., 2000; Heathwaite and Dils, 2000; Gentry et al., 2007; Van Esbroeck et al., 2015), and should be avoided when tile drains are likely to be active. This study suggests that the potential is greatest when soil moisture is high, during the fall before rain events and prior to seasonal snow cover.

The second manuscript of this thesis explored the threshold conditions that triggered tile drainage and P-export as well as the possibility of predicting P losses after baseline data has been established. It was found that antecedent soil moisture and precipitation inputs are primary factors in driving runoff generation and event magnitude to be closely tied to event P-losses. Tile flow is only triggered after a threshold soil moisture was reached during a precipitation or melt event, depending on available soil moisture storage. Runoff ratios correlating with VWC have been found in previous studies (Wei et al., 2007; Brocca et al., 2009; Radatz et al., 2013). Seasonal differences in VWC, and thus soil storage capacity correlate with differences in tile drainage. During the growing season when the soil is dry, precipitation inputs must satisfy the much larger soil moisture deficit before tile flow can occur. Therefore, events during these months are less common and only very large inputs trigger flow. Other studies have also found similar correlations between moisture and flow (Katz and Thompson, 1986; Berkowitz and Ewing, 1998). This suggest that crude hydrological and nutrient responses from drainage tiles from some sites can potentially be predicted using easily monitored metrics such as soil moisture and precipitation after baseline conditions at a site have been established. This may be useful in modelling efforts; which are currently lacking for P (Kleinman et al., 2015b).

The findings of this research can be used to further inform and improve BMPs in southern Ontario landscapes that have similar soil types and climatic regimes. As well, the results of our study may be useful for site managers and developing and improving tile drain and P-loss modeling, which can be used to strengthen BMPs (Hively et al., 2006; Kleinman et al., 2015a).

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