Vegetated Buffer Strip Efficacy for Phosphorus Reduction in a Cold Climate Agricultural Watershed

by

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Abstract

A vegetated buffer strip (VBS) is a common measure implemented in agricultural landscapes to improve water quality. However, much of the evidence to support their effectiveness comes from warm regions dominated by rainfall driven runoff. This study assessed the performance of VBS plots and compared them to annual crop strips to reduce phosphorus (P) levels in runoff in the cold climate of the Canadian prairies. Analysis of water samples from 22 events during the study indicated no significant difference in the inflow and outflow concentrations of total dissolved phosphorus (TDP) or total phosphorus (TP) for either the VBS or the annual crop strips. While the VBS plots had little effect on TDP or TP during the spring, they performed better during the growing season reducing mean TP concentrations in five out of seven, or 71%, of these events. The VBS plots did not perform as well during the fall events, with the overall mean TP concentration in runoff increasing after flowing through the buffers during this time period. Although mean soil P levels in the VBS plots increased over the course of the study, the difference was not statistically significant. Vegetation within the VBS represents a substantial pool of P, with the harvestable portion containing 3.33 kg/ha of TP and the post-harvest plant residues containing 1.71 kg/ha of TP.

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List of Acronyms

BI - buffer inflow

BO – buffer outflow

CI - control inflow

CO – control outflow

N – nitrogen

OM - organic matter

P - phosphorus

TDP - total dissolved phosphorus

TP - total phosphorus

TSS - total suspended solids

VBS - vegetated buffer strip

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1.1. Introduction

1.1.1. Cultural eutrophication of water bodies

Cultural eutrophication, or excessive plant growth resulting from nutrient enrichment from human activity, is the primary concern for most surface waters in the world today (Harper, 1992; Smith and Schindler, 2009). Eutrophication is associated with the transfer of nutrients such as nitrogen and phosphorus (P) from land to water bodies and is exacerbated by intense upstream agricultural land use activities. The two main forms of P in aquatic systems are dissolved and particulate and the proportion of these forms is greatly dependent on the source and transport mechanisms. Higher proportions of particulate phosphorus in water are generally related to organic matter and sediment sources and erosion processes that carry soil and associated P. Dissolved phosphorus can be associated with decomposing organic matter as well as inorganic fertilizers and can result from the desorption, or release, of P from soils and sediments. Soluble inorganic orthophosphates can be transferred directly from soils to runoff and transported to nearby waterways and enter aquatic systems. Issues commonly associated with eutrophication include excessive algal growth, surface scums, increased suspended solids, and decreased light penetration and can lead to dissolved oxygen depletion, fish kills, odour issues, the release of harmful algal toxins and water use restrictions (Schindler, 1977; Sharpley et al., 1994; Migliaccio et al., 2007; Reid et al., 2016).

1.1.2. Eutrophication of Lake Winnipeg

Lake Winnipeg, the tenth largest freshwater lake in the world, is located in Manitoba, Canada, and has been classified as either eutrophic or hypereutrophic due to its high level of nutrient enrichment (Levesque and Page, 2011). Algal abundance and nutrient loading to the lake, mainly from the Red River, has increased over several decades and has been linked to intensified agricultural and other human activities in its watershed (Kling, 1998; Jones and Armstrong, 2001; Bunting et al., 2011). Concerns for the health of the lake have increased since the early 1990s due to frequent and extensive blooms of cyanobacteria, or blue-green algae (McCullough, 2009).

1.1.3. Increasing runoff levels

Land use change in the Northern Great Plains since European settlement has been dramatic, where vast tracts of forests and grasslands have been cleared or plowed to make the land suitable for agricultural production. Hanuta (2006) noted in a study of land cover changes in southern Manitoba since the 19th century that nearly all of the original grasslands have disappeared, wetland areas have decreased by over 90% and treed areas have diminished by over 70%. These findings are supported by additional studies of land use in watersheds of the Red River and its tributaries, including the Assiniboine and Souris Rivers extending into Saskatchewan and the United States, that suggest this predominantly agricultural area has lost over 80% of pre-settlement wetlands (Voora and Venema, 2008; Melles et al., 2010). Although these land use trends began with the arrival of European settlers in the 19th century, there is considerable evidence that much of the more pronounced changes have occurred in recent decades. It is estimated that between 1985 and 2001, over 200,000 ha of wetlands were lost in the Canadian prairie pothole region that encompasses the majority of agricultural land in the provinces of Manitoba, Saskatchewan and Alberta, with over 60% of these losses due to drainage and conversion to cultivated cropping systems (Watmough and Schmoll, 2007). A comparison of Census of Agriculture records from 2006 to 2011 indicate that woodland and wetland features on land managed by agricultural producers in Canada during this five year period decreased by nearly 9% (Statistics Canada, 2011). These changes in land use and corresponding increases in drainage activity have had a profound impact on the hydrology of this region (Voora and Venema, 2008; Melles et al., 2010).

Increased precipitation levels since the 1990s, often referred to as a “wet cycle”, have contributed to increased runoff and more frequent spring floods in the Red River Basin (McCullough et al., 2012; Schindler et al., 2012). The combination of increased runoff and intensification of agricultural activities during this time period have contributed to increased transfer of nutrients from land to surface waters that ultimately enter Lake Winnipeg (Bunting et al., 2011; McCullough et al., 2012). The increased river flows and flood frequency in the Red River Basin have not only increased nutrient loads from higher river discharge but also due to substantial increases in nutrient concentrations during these extreme flow events. Total P concentrations in the river doubled during the 1990s “wet cycle” leading to significant increases in downstream P loading via the Red River to Lake Winnipeg and this trend continued into the 2000s (McCullough et al., 2012; Schindler et al., 2012). These findings are supported by Reid et al. (2016), who examined trends in the risk of P contamination to surface water from 1981 to 2011. They reported that the main factor leading to an increased risk of P contamination to surface water in much of the Canadian Prairies in 2011 was due to high runoff levels from snowmelt and spring rains.

1.1.4. Agricultural non-point source phosphorus

Due to the importance of P and its linkages to eutrophication, algal growth, and aquatic health impairment, an emphasis has been placed on reducing P loading to surface water bodies throughout many parts of North America (e.g. Great Lakes Commission, 2012; Schindler et al., 2012). These efforts have not been confined to North America as efforts in other parts of the world are underway to address nutrient enrichment of water bodies (e.g. Withers and Haygarth, 2007; Ulén et al., 2012). There is considerable evidence that agricultural activities have contributed to increases in P concentrations and loads in water bodies. Frossard et al. (2000) demonstrated a link between problematic levels of P loading and extraneous application of P fertilizers. Areas with intensive cropping and livestock production have been shown to be areas of particular concern for P losses (Sharpley et al., 1994). Applications of fertilizers, including livestock manure and synthetic blends, containing more P than crops can remove during the growing season can lead to soil P saturation, thereby increasing the risk of non-point source P delivery to waterbodies from runoff (Reid et al., 2016).

Dungait et al. (2012) reported that although P export from agriculture is generally considered small (usually less than 1 to 6 kg ha^{-1}) in comparison to the amount of P in the soil and plant pools, extreme losses (e.g. up to 30 kg P ha^{-1}) can occur during prolonged storms and runoff events. Even P losses that are considered small in agricultural terms can contribute to eutrophication of surface waters, particularly in slow flowing rivers and streams typical of the Red River Basin (Johnston and Dawson, 2005). The P yield, or loading per surface area (kg ha^{-1}), of areas of southern Manitoba including the Red River Basin, is five times that of the Lake Winnipeg Watershed as a whole, suggesting this region is worthy of particular attention for mitigation strategies (Roy et al., 2007). Due to the relatively small contribution of point sources of P to Lake Winnipeg (i.e. approximately 10%), emphasis should be placed on areas with high non-point sources of P like the Red River Basin in southern Manitoba (Lake Winnipeg Stewardship Board, 2006).

Multiple studies have documented increased nutrient loading from the Red River over the past five decades and suggest that intensified agricultural activities are at least partly to blame

(Kling, 1998; Jones and Armstrong, 2001; Bunting et al., 2011). A study that employed the SPARROW (SPAtially Referenced Regressions On Watershed attributes) model using data circa 2002 suggested that agriculture was the main source of P in the Red River Basin (Benoy et al., 2016). The main agricultural sources of P in the Red River Basin stem from the use of synthetic fertilizers and manure, and application rates of these nutrient sources have been increasing since the 1980s (Dorff and Beaulieu, 2011; Yates et al., 2012). Reid et al. (2016) calculated P balances based on the Canadian Census of Agriculture from 1981 to 2011. They reported that the Prairie Provinces exhibited negative P balances in most agricultural watersheds in the 1980s and early 1990s, but due to increases in livestock numbers and fertilizer use in recent years many watersheds began to report P surpluses, with the greatest increases found in Manitoba. This helps explain increasing trends in P losses from farmland in this region since the early 1990s.

1.1.5. Practices to reduce agricultural non-point source nutrient losses

With mounting evidence in the early part of the 21st century that agricultural P is a significant contributor to the eutrophication of Lake Winnipeg, numerous studies have been initiated to better understand and address this problem. Lobb et al. (2012) investigated the mechanisms and processes by which P is transferred from land to surface waters and examined a variety of management practices that were thought to address this problem. Other studies demonstrated that erosion risks, including wind, water, and tillage erosion, have decreased during the 1980s and 1990s (Lobb et al. 2003; McConkey et al. 2012). This decrease has primarily been attributed to the widespread adoption of conservation tillage practices in most agricultural regions since the 1980s. Lobb et al. (2012) and Liu et al. (2014) conducted studies to characterize sources of sediment and associated P and estimate levels of non-point agriculture sources in tributaries of the Red River in southern Manitoba. Li et al. (2011) studied the effect of multiple agricultural practices in two small watersheds in the Red River Basin and concluded the cumulative impact on nutrient export was substantial although most of the reduction was attributed to a single practice, a holding pond to treat runoff from a livestock yard. In the same watershed, Tiessen et al. (2010) showed that conservation tillage can result in increased P losses while Tiessen et al. (2011) showed that small headwater storage dams are effective in reducing nutrient loads. With much of the research on reducing non-point source agricultural nutrient losses in this region confined to the same relatively small study area (i.e. South Tobacco Creek Watershed) and limited number of agricultural practices studied, a substantial gap exists in understanding the effect of agricultural management practices in the cold climate of the Canadian Prairie region. One such practice that currently has little evidence to support its efficacy for P loss reduction in this region is vegetated buffer strips (VBS).

1.1.6. Vegetated buffer strips description

Vegetated buffer strips (VBS), often referred to simply as a buffer or filter strip, is described, in general terms, as a strip or band of permanent herbaceous vegetation that removes contaminants from overland and shallow subsurface flow (Fischer and Fischenich, 2000; USDA-NRCS, 2010). They are designed to slow runoff, intercept sediment, and increase infiltration rates (Muscutt et al., 1993; Norris, 1993; Haycock et al., 1997; Kronvang et al., 2000, 2005; Lacas et al., 2005; Dorioz et al., 2006; Muenz et al., 2006). Nutrients are assimilated into VBS vegetation through uptake from soil (Fischer and Fischenich, 2000). When VBS are established in-field, also known as vegetative barriers, they can be effective at reducing concentrated flow and mitigating the development of ephemeral gullies (Lowrance et al., 2002). This type of implementation is intended to mitigate soil erosion and the mobilization of contaminants at the source rather than a final treatment at the edge of a field or adjacent to a waterway (Dabney et al., 2006). For this paper, VBS will include edge-of field, riparian buffers, and in-field vegetative barriers and buffer strips as their functions and intended purpose are similar.

Vegetated buffer strips are common in parts of Europe and North America mainly due to ease of implementation and low cost (Hickey and Doran, 2004; Dorioz et al., 2006). Some jurisdictions have made these practices mandatory (e.g. Minnesota and Vermont in the USA). Although they have been promoted for water quality improvements in agricultural watersheds in Manitoba (e.g. Canada-Manitoba Farm Stewardship Program), their efficacy for P retention in this region remains uncertain.

1.2. Vegetated buffer strip performance for phosphorus retention: a review

Vegetated buffer strips have long been studied and recommended around the world for contaminant interception, including for P retention in agricultural landscapes. Many studies have supported the use of this practice in a variety of agricultural regions and climates including reviews that assessed multiple studies in Western Europe, Scandinavia, and North America (Kronvang et al., 2005; Dorioz et al., 2006; Muenz et al., 2006; Hoffmann et al., 2009). Numerous studies reported that properly designed and implemented VBS can achieve P retention rates of over 50% (Dillaha et al. 1988, 1989; Barfield et al., 1998; Schmitt et al., 1999; Iowa State University, 2000; Uusi-Kämppä et al., 2000; Abu-Zreig et al., 2003; Gitau et al., 2005; Dorioz et al., 2006; Duchemin and Hogue, 2009), while other studies report more modest reductions of less than 30% (Magette et al., 1989; Chase et al., 2016). Chase et al. (2016) studied a variety of watersheds in New Brunswick, Canada, and reported significantly lower dissolved phosphate concentrations in watersheds with higher ratios of permanent riparian vegetation to agricultural intensity. Other studies were not as conclusive, suggesting that VBS may increase P delivery or that their efficiency was highly dependent on the structure and location of the VBS (Norris, 1993; Dosskey et al., 2007; Hoffmann et al., 2009; Roberts et al., 2012). Hoffmann et al. (2009) conducted an extensive review that included an analysis of research sites and studies from Canada, USA, and Europe. The 10 VBS studies that were part of the review reported variable retention efficiency for total P (32 to 93%) and even higher variability for dissolved reactive P retention (-71 to 95%).

1.3. Vegetated buffer strip phosphorus retention mechanisms and performance factors

The amount of P retention in a VBS is generally governed by physical and biogeochemical processes. The dominant physical factor that affects P retention is the velocity of overland flow through the VBS. Characteristics that have been widely reported to significantly impact flow velocity, thereby affecting VBS P retention, include such physical parameters as width (Dillaha et al., 1988; Magette et al., 1989; Coyne et al., 1995; Schmitt et al., 1999; Dosskey, 2001; Abu-Zreig et al., 2003; Lee et al., 2003; Sheppard et al., 2006; Deeks et al., 2012; Stewart et al., 2011), slope (Dillaha, 1990; Schmitt et al., 1999; Dosskey, 2001; Abu-Zreig et al., 2003; Gitau et al., 2005; Lacas et al., 2005), and surface roughness which is greatly dependent on vegetation characteristics (Norris, 1993; Abu-Zreig et al., 2003; Uusi-Kämppä, 2005; Dosskey et al., 2007; Duchemin and Hogue, 2009; Deeks et al., 2012). Although VBS width is the most widely accepted factor influencing P retention performance, it has been argued that there are limits or thresholds and that most P trapping and retention occurs in the upslope or leading edge of the buffer strip (Uusi-Kämppä et al., 2000; Syversen et al., 2001; Hook, 2002).

Reduced overland flow velocities due to VBS implementation will influence other key physical processes that impact P retention. Many studies cite enhanced filtration and sedimentation as the key mechanism for P retention in a VBS (Dabney et al., 2006; Sheppard et al., 2006; Hoffmann et al., 2009; Stewart et al., 2011). Slowing runoff leads to increased infiltration rates and enhances P retention in VBS soils (Dillaha, 1990; Norris, 1993; Barfield et al.,1998; Dosskey, 2001; Gitau et al., 2005; Syversen, 2005; Dabney et al., 2006; Sheppard et al., 2006). However, infiltration rates are also significantly affected by texture, structure and the permeability and porosity of the VBS soils and can be greatly dependent on antecedent moisture conditions (Magette et al., 1989; Coyne et al., 1998). Reductions in flow velocity will also increase residence time in the VBS, increasing soil-plant contact with runoff waters and greater potential for soil adsorption and plant assimilation of P (Woltemade, 2000; Reinhardt et al., 2005; Syversen, 2005; Dabney et al., 2006; Knox et al., 2008). Changes in infiltration rates can also alter flow paths with increased infiltration leading to greater subsurface flow rates and solute transport and reduced overland flow (Hoffmann et al., 2009). Reduced runoff velocity has been demonstrated to reduce erosion rates and related export of soil particles and sediment-bound P (Syversen, 2005; Dabney et al., 2006).

The type of flow within a VBS is an important factor in determining its P retention efficiency. VBS have been reported to be more effective with diffuse shallow flow as opposed to deeper concentrated flow. The ratio of flow depth to vegetation height, or degree of submerged vegetation, in a VBS has been correlated to its P trapping efficiency (Owens et al. 2007; Pankau et al., 2012). Characteristics that determine the likelihood of concentrated flow include the drainage area and flow length for the site (USDA-NRCS-Minnesota, 2010).

There are many biogeochemical processes and factors that influence the P retention efficiency in a VBS. Soil physical and chemical properties determine its P saturation level. The degree of soil P saturation and binding capacity have been shown to affect the equilibrium runoff P concentration, where levels above this equilibrium will lead to P retention in the soil (Richardson, 1985; Dillaha et al., 1989; Lee et al., 1989; Pant et al., 2002; Pant and Reddy, 2003;

Liikanen et al., 2004; Hoffmann et al., 2009). Conversely, P concentrations in the runoff below the equilibrium level can result in P leaching from the soil to runoff waters, thereby causing P concentrations to increase as runoff passes through the VBS. Consequently, researchers have suggested that not only the soil P status but also the hydraulic loading rate, or inflow P concentrations, will have a substantial impact on the P retention efficiency of a VBS (Schellinger and Clausen, 1992; Jordan et al., 2003; Koskiaho et al., 2003). Other soil properties like organic matter content will affect the water holding capacity of the VBS soils and can affect the amount of runoff reduction and associated P retention (Hudson, 1994). Many studies have also investigated the impact of P forms in the runoff water entering a VBS. There is a significant body of evidence that suggests the efficiency of the VBS is influenced by the proportions of dissolved and particulate P in the runoff, with greater variability and uncertainty associated with retention of dissolved P (Dillaha et al., 1988, 1989; Norris, 1993; Schmitt et al., 1999; Lee et al., 2000; Uusi-Kämppä et al., 2000; Gitau et al., 2005; Nakamura and Yamada, 2005).

Plant uptake of P is an important biological process associated with VBS P retention. Plants sequester P from soil through their root systems. However, retention of P in vegetation can be temporary as plant tissues can also leach or release P under certain conditions (Syversen, 2005; Uusi-Kämppä, 2005; Dabney et al., 2006; Duchemin and Hogue, 2009; Hoffmann et al., 2009). Cells in plants that undergo senescence and begin to decay can rupture and release P to runoff (Liu et al., 2013a).

Vegetated buffer strip performance is dependent on its age, measured as its time since establishment. When cropland is converted to a VBS, the cessation of tillage and establishment of permanent vegetation will change soil properties over time (Dick et al., 1991; Weinhold and Tanaka, 2000; Karlen et al., 2013). However, changes in vegetation density, soil structure, and soil chemistry that are important factors for P retention take time. Some studies suggest significant changes in soil structure and infiltration characteristics can be observed within four years (Weinhold and Tanaka, 2000), while other studies suggest the full impact of a VBS on these properties may not be realized for 10 years or more (McCollum, 1991; Dosskey et al., 2007; Meals et al., 2010; Liu et al., 2014).

1.4. Cold climate vegetated buffer strip performance uncertainty

1.4.1. Cold climate vegetated buffer strip phosphorus retention research

Although many studies have supported the use of VBS for P retention, including numerous scientific reviews (Hickey and Doran, 2004; Dabney et al., 2006; Dorioz et al., 2006; Liu et al., 2008; Hoffmann et al., 2009; Yuan et al., 2009; Dosskey et al,. 2010; Roberts et al., 2012), there is little evidence to suggest they are as effective in cold climates, particularly during snowmelt runoff conditions. Research on VBS sites in cold regions, with extended periods below 0 ^{o}C when precipitation occurs mainly as snow, has shown that P retention can be highly variable under these conditions. Sheppard et al. (2006) investigated VBS sites in Manitoba, Canada, and reported that P concentrations were reduced in only 50% of the study cases, while 18% of the cases showed an increase in P concentration. Subsequent research building on the previous studies in this region supported these findings, reporting no significant difference in P concentrations passing through several VBS sites (Sheppard et al., 2012; Habibiandehkordi et al., 2017). Similar findings have been reported in other cold climate regions. In a 10 year study in Finland, Uusi-Kämppä (2005) found increased reactive P export from VBS sites. This is supported by studies from Vermont, USA, that have observed reduced P retention in VBS during snowmelt (Schwer and Clausen, 1989; Schellinger and Clausen, 1992).

1.4.2. Snowmelt runoff and frozen soil conditions

In cold regions, winter precipitation usually falls in the form of snow that can accumulate over several months. Melting of the snowpack can produce substantial amounts of runoff in the spring in these regions. For example, in the Canadian Prairies snowmelt runoff, on average, exceeds rainfall-induced runoff with most studies suggesting 70-80% of the annual runoff in this region is derived from snowmelt (Nicholaichuk, 1967; Granger et al., 1984; Glozier et al., 2006; Little et al., 2007; Shrestha et al., 2012; Liu et al., 2014; Cordeiro et al., 2017). Other cold regions, including northern United States and Scandinavian countries, also experience significant amounts of snowmelt runoff (Hansen et al., 2000; Syversen, 2002; Uusi-Kämppä, 2005). High proportions of runoff during snowmelt in cold regions is attributed to reduced infiltration caused by either frozen ground or saturated soils (Macrae et al., 2010; Li et al., 2011; Su et al., 2011). Because snowmelt events usually last longer and are typically more significant than rainfall events in cold climates, they can lead to channelized concentrated flow conditions as opposed to diffuse, shallow flow. Vegetation in the VBS is often flattened and submerged during snowmelt, reducing surface roughness and filtering capacity. Under these conditions where runoff is concentrated in discrete channels on flattened and submerged vegetation, the P retention capacity of VBS is diminished (Owens et al., 2007; Lobb et al., 2012; Pankau et al., 2012; Habibiandehkordi et al., 2017). Soils in cold regions are usually frozen for long periods during winter months and often remain frozen during portions of the snowmelt period. Frozen soils have extremely low permeability, leading to negligible infiltration and reduced P retention potential (Gitau et al., 2005; Surridge et al., 2007; Amarawansha et al., 2015).

1.4.3. Biogeochemical processes during snowmelt

Many of the biogeochemical processes that are critical for effective P retention in VBS are affected by temperature. Due to the lack of runoff infiltration into frozen soils, there is reduced potential for adsorption of P within the soil (Sheppard et al., 2012). Biological assimilation and uptake of P is limited during the cold snowmelt runoff period when microbes are less active and plants are dormant (Uusi-Kämppä, 2005; Sheppard et al., 2012). Decaying vegetation leaches substantial amounts of P during runoff events (Hickey and Doran, 2004), predominately in dissolved form (Ulén, 1984). Increased levels of dissolved P are released from vegetation that has been subjected to freezing and thawing, a frequent occurrence during spring snowmelt conditions (Bechmann et al., 2005; Roberson et al., 2007; Øgaard, 2015). This phenomenon can cause a VBS to become a source of P and increase delivery of P to runoff waters instead of decreasing it (Uusi-Kämppä, 2005).

1.4.4. Proportion of dissolved phosphorus

In cold regions, like the Canadian Prairies, where snowmelt runoff occurs on frozen soils over level or gently sloping, undulating topography, water erosion potential is reduced leading to lower sediment-bound or particulate P in runoff. Salvano et al. (2009) demonstrated that total P concentrations in agricultural watersheds in Manitoba, Canada, were poorly correlated with erosion and that other processes were responsible for most of the P delivered to waterways. Decomposing vegetative residues, especially when frozen and thawed, represent a substantial source of P in the dissolved form (Ulén, 1984). These factors lead to high proportions of dissolved P in runoff in cold climates, especially during snowmelt conditions (e.g. Tiessen et al., 2010; Cade-Menun et al., 2013; Liu et al., 2014). The high proportion of dissolved P is problematic as one of the main processes for P retention in a VBS is sedimentation (Hoffmann et al., 2009). VBS studies commonly report high efficiencies for trapping sediment and particulate P, including research in cold climates (Sheppard et al., 2006; Stewart et al., 2011) and even with the implementation of very narrow strips (e.g. less than 1 m) (Dabney et al., 2006). However, in a review of VBS performance by Hoffmann et al. (2009), dissolved reactive P reduction was highly variable, ranging from -71% to 95%, in some cases the dissolved reactive P levels in VBS runoff increased. This was supported by Gitau et al. (2005), where data from several studies were combined, suggesting highly variable dissolved P reductions ranging from -56% to 59%.

1.5. Research gaps

Very few studies have investigated seasonal differences in VBS performance for P retention in cold climates. A significant gap in knowledge exists about how a VBS functions during snowmelt runoff and how that compares to rain events in the spring, summer (active growing season), and during the period when the vegetation begins to senesce and becomes dormant in the late summer and fall.

There has been very little research in cold climates that track spatial and temporal patterns of soil and vegetation P levels through these seasons and examine the impact of landscape position on P dynamics. An improved understanding of these patterns and conditions will help understand why VBS can be a source of P at certain times of the year, and sinks for retaining P at others.

Another limitation in past research is that few studies have compared the performance of a VBS treatment to annually cropped strips as controls. Agricultural crops typically have high P requirements and uptake rates, but there is a lack of research that compares the efficacy of these crops grown as strips for runoff P retention in cold climates.

1.6. Research objectives

This study located at Agriculture and Agri-Food Canada's Morden Research and Development Centre within the Red River Basin of Manitoba, Canada, was initiated to address the research gaps mentioned above. The research is organized under three main themes:

1. Assessment of vegetated buffer strip efficacy for surface runoff P retention in cold climate agricultural watersheds
2. Assessment of spatial and temporal patterns of soil P in vegetated buffer strips in cold climates
3. Assessment of spatial and temporal patterns of vegetation P in vegetated buffer strips in cold climates

Figure 1.1 summarizes these three themes and their associated research questions, objectives and general methods. The first theme is explored in Chapter 2 while the second and third themes are combined and presented together in Chapter 3. These two chapters are written in the form of journal manuscripts. Chapter 4 is a synthesis of the research, including a discussion of study limitations, and implications for future VBS research, designs and management schemes.

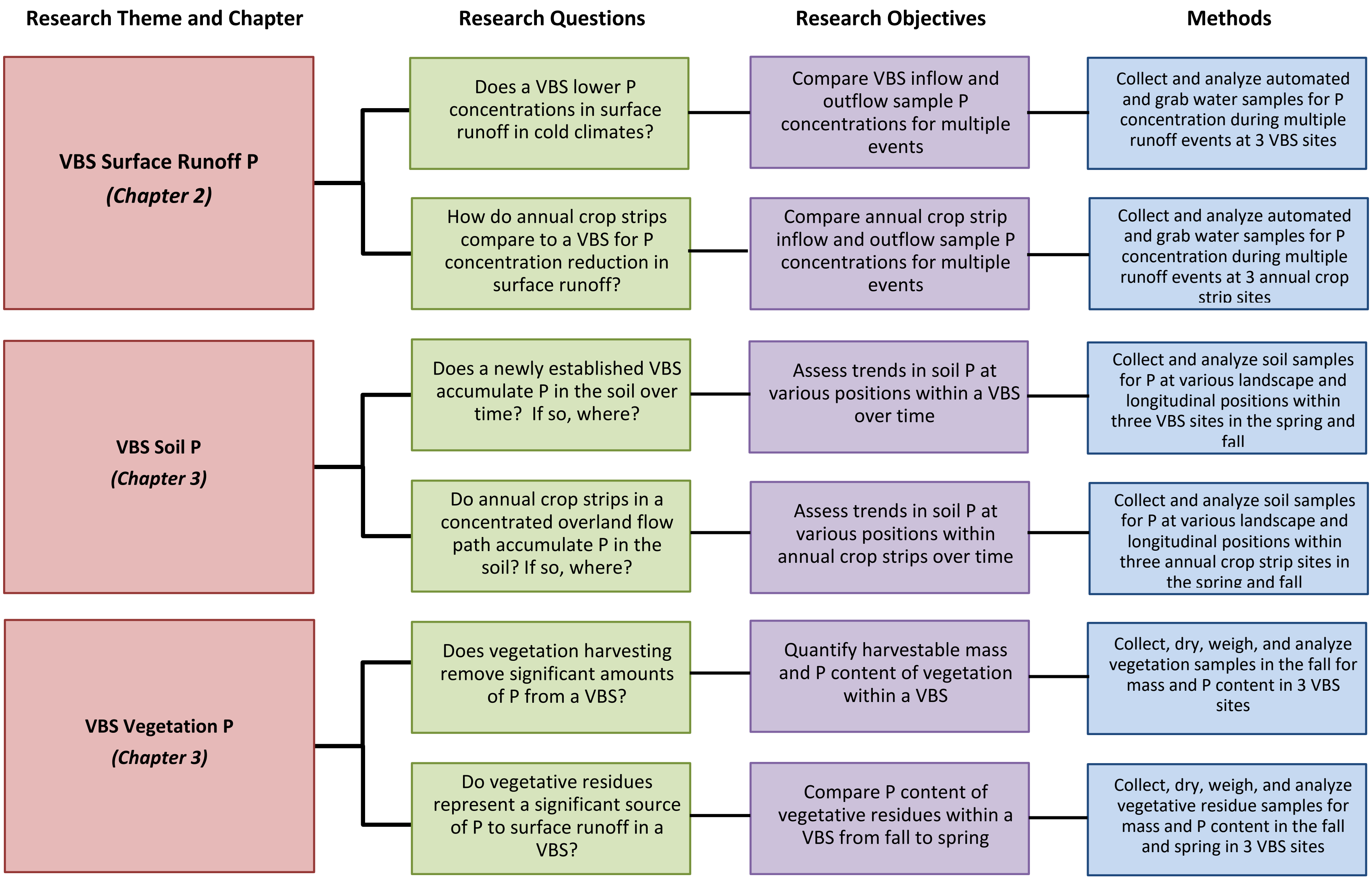

Figure 1.1. Research themes, questions, objectives and methods

2. Efficacy of vegetated buffer strips for surface runoff P retention in cold climate agricultural watersheds

2.1. Introduction

Nutrient enrichment leading to the declining health of water bodies is an increasingly important issue around the world. In many aquatic systems, phosphorus (P) has been identified as the limiting nutrient and main contributor to anthropogenic eutrophication (Schindler 1977). As a result, P has become the focus of research and policies designed to improve the health of water bodies around the world, such as Lake Winnipeg and Lake Erie in North America (Sharpley et al., 1994; Jones and Armstrong, 2001; LWSB 2006; Bunting et al., 2011; Great Lakes Commission, 2012; McCullough et al., 2012; Schindler et al., 2012) and many freshwater and coastal systems in Europe (Withers and Haygarth, 2007). Non-point sources of P, including synthetic fertilizers and manure that are transported in the runoff from farmland, are increasingly being identified as major contributors in agricultural watersheds (e.g. Sharpley et al., 1994; Frossard et al., 2000; Redi et al., 2016).

Vegetated buffer strips (VBS) have proven to be effective for P retention – and thus reduced delivery to surface waters – in rainfall runoff or simulated rainfall experiments. Significant retention of P in VBS, ranging from 20% - 89%, has been reported by numerous studies under these conditions (Dillaha et al., 1989; Magette et al., 1989; Parsons et al., 1991; Schmitt et al., 1999; Abu-Zrieg et al., 2003). However, results have been much more variable in studies conducted outside the summer or growing season in cold climates. The variable performance for P retention during snowmelt conditions, with frozen soil conditions and high levels of dissolved P, has been reported in studies in Finland (Uusi-Kamppa, 2005), the northern United States (Schellinger and Clausen, 1992), and Canada (Habibiandehkordi et al., 2017). With multiple studies suggesting poor or uncertain performance for VBS to retain P in cold climates (see the review by Kieta et al., 2018), there is a need for further research to identify the conditions, factors, and processes that determine their efficacy with an emphasis on seasonality, specifically the non-growing season when VBS are likely to operate differently than in the growing season. For example, due to a lack of fall events, Habibiandehkordi et al. (2017) combined the data collected in summer and fall into one group, thereby limiting the implications of the findings in terms of management recommendations. Previous assumptions related to VBS designs also need to be evaluated in cold climate conditions. For example, the length of the VBS strips in previous cold climate studies has been rather small, typically less than or equal to 10 m (Schellinger and Clausen (1992) = 7.6m; Uusi-Kamppa (2005) = 10m; Habibiandehkordi et al. (2017) = 4.5m). Habibiandehkordi et al. (2017) relied on a "first flush" sampling protocol, yielding only a single water sample at the beginning of each runoff event. Due to variability in nutrient and sediment concentrations during a runoff event, event mean concentrations derived from multiple samples would be required to reduce the variability and bias of a single sample taken only at the beginning of an event. Although considerable attention has been placed on VBS for P retention, annual crop systems also have the potential to be both sources and sinks for P in agricultural regions. Annual export of P in runoff from cropland is highly variable and ranges from about 0.2 to 6 kg TP/ha/year (Dungait et al., 2012; Van Esbroeck et al., 2015). However, the capacity for annual crops to uptake and assimilate P has been reported to be as high as 30 kg/ha/year for corn crops in Manitoba, Canada (Heard and Hay, 2004).

The objective of this study was to assess VBS performance for P retention, in terms of reduction in P concentration as runoff passes through the VBS over multiple seasons, in a cold climate agricultural landscape within the Red River Basin of Manitoba, Canada. A second research objective was related to comparing the performance of the VBS treatments in terms of reduction in runoff P concentration to that of a control or pre-treatment condition, in this case strips of annual crop.

2.2. Methods

2.2.1. Site description

The study area (Agriculture and Agri-Food Canada's Morden Research and Development Centre) is located in the Red River Basin, part of the Lake Winnipeg Watershed (Figure 2.1). The site is on the western boundary of the Manitoba Lowland physiographic region, an area of low relief below the Manitoba Escarpment. The physiography of the region is heavily influenced by glaciation. At the end of the last ice age, as the water in glacial Lake Agassiz receded, wave action along the shore line caused the formation of beach ridges and modifications to earlier deposits. Where streams emerged from the Manitoba Escarpment, alluvial plains were formed.

The land in the 20 ha study area is predominantly used for annual crop production, mainly cereals, pulses, and oilseeds. Three separate sites for VBS and annual crop (i.e. "control") strip pairs were located upstream of water bodies (i.e. ponds or an ephemeral stream) (Figure 2.2).

Elevation in the study area ranges from a high of about 297 m in the west-central part of the study area to a low of about 294 m in the south-east corner (Figure 2.3). The land is gently sloping towards the south and east with an average gradient of about 0.25%. The topography is mainly level to nearly level (0 – 2% slope) with some very gently sloping areas (2 - 5% slope). Some strongly sloping areas (above 10% slope) are found adjacent to waterways on streambanks but do not account for a substantial portion of the study area (Figure 2.4).

The study area is located in the Winkler Ecodistrict of the Lake Manitoba Plain Ecoregion within the Prairie Ecozone. Data from an on-site weather station over a 30 year period (1981 to 2010) were used to summarize the climate. The mean annual temperature is 4.0°C. Daily average temperature ranges from 20.0°C in July to -14.6°C in January. Mean annual precipitation for the area is 540.8 mm, consisting on average of 426.5 mm of rain and 116 cm of snow. Monthly averages for precipitation range from 19 mm in January and February to 93 mm in June (Table 2.1). Snow typically begins to accumulate in November with snowmelt commonly occurring during March and April.

The soil series found within the study area include Hochfeld, Edenburg, Eigenhof, Rosengart, Rignold, Graysville, Neuenberg, and Chortitz series (Figure 2.5) (Smith et al., 1973). The soils in the VBS sites (B1, B2, and B3) are dominated by Hochfeld, Chortitz, Graysville, and Neuenberg soil series developed on moderately to strongly calcareous, loamy (very fine sandy loam, silty loam, or loam) fluvial and lacustrine sediments grading to moderately calcareous, sandy sediments. Site B2 had topsoil excavated prior to construction, exposing coarse subsoil material.

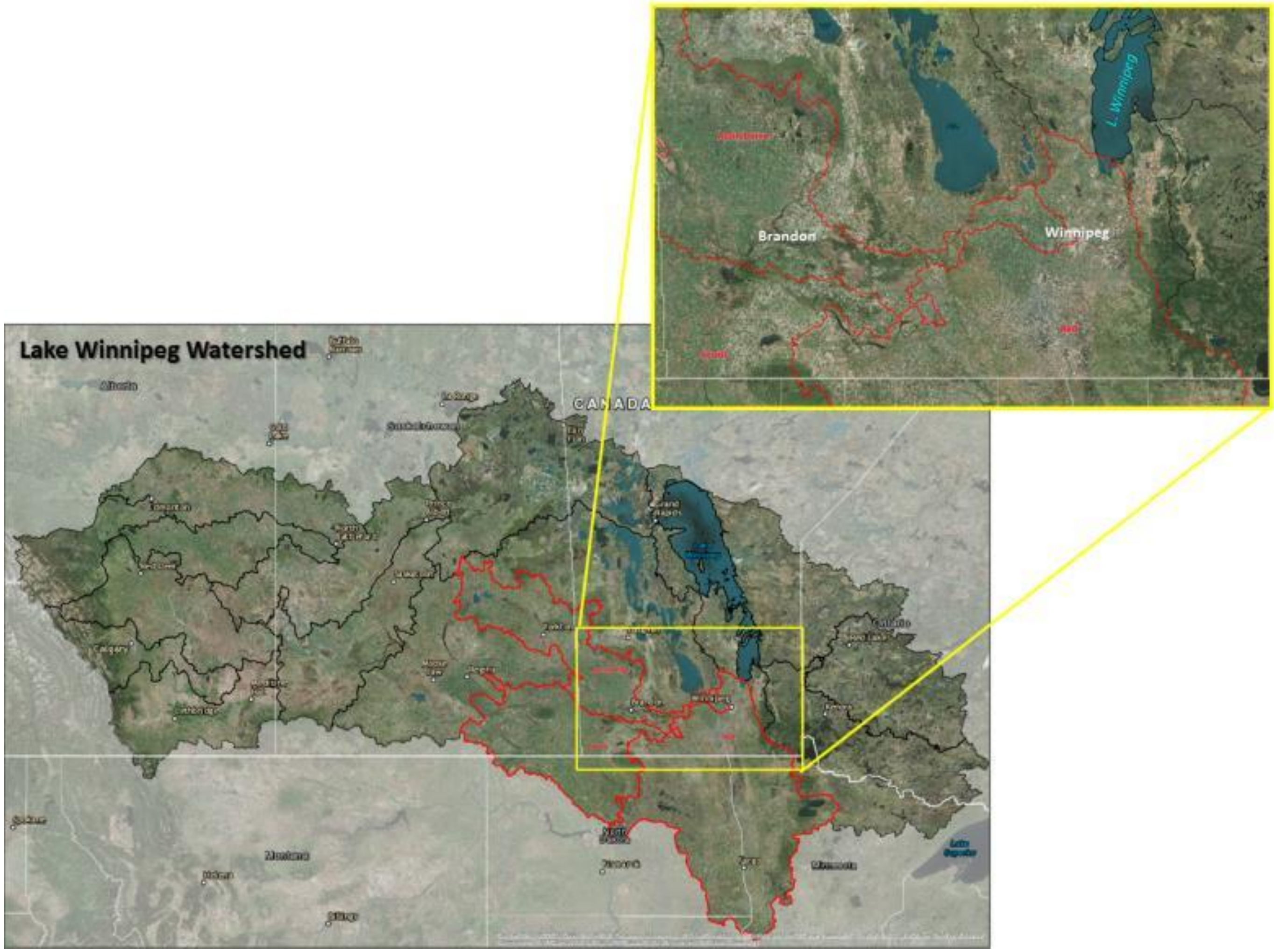

Figure 2.1. Lake Winnipeg Watershed and Major River Basins in Southern Manitoba, Canada. Sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA FSA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community

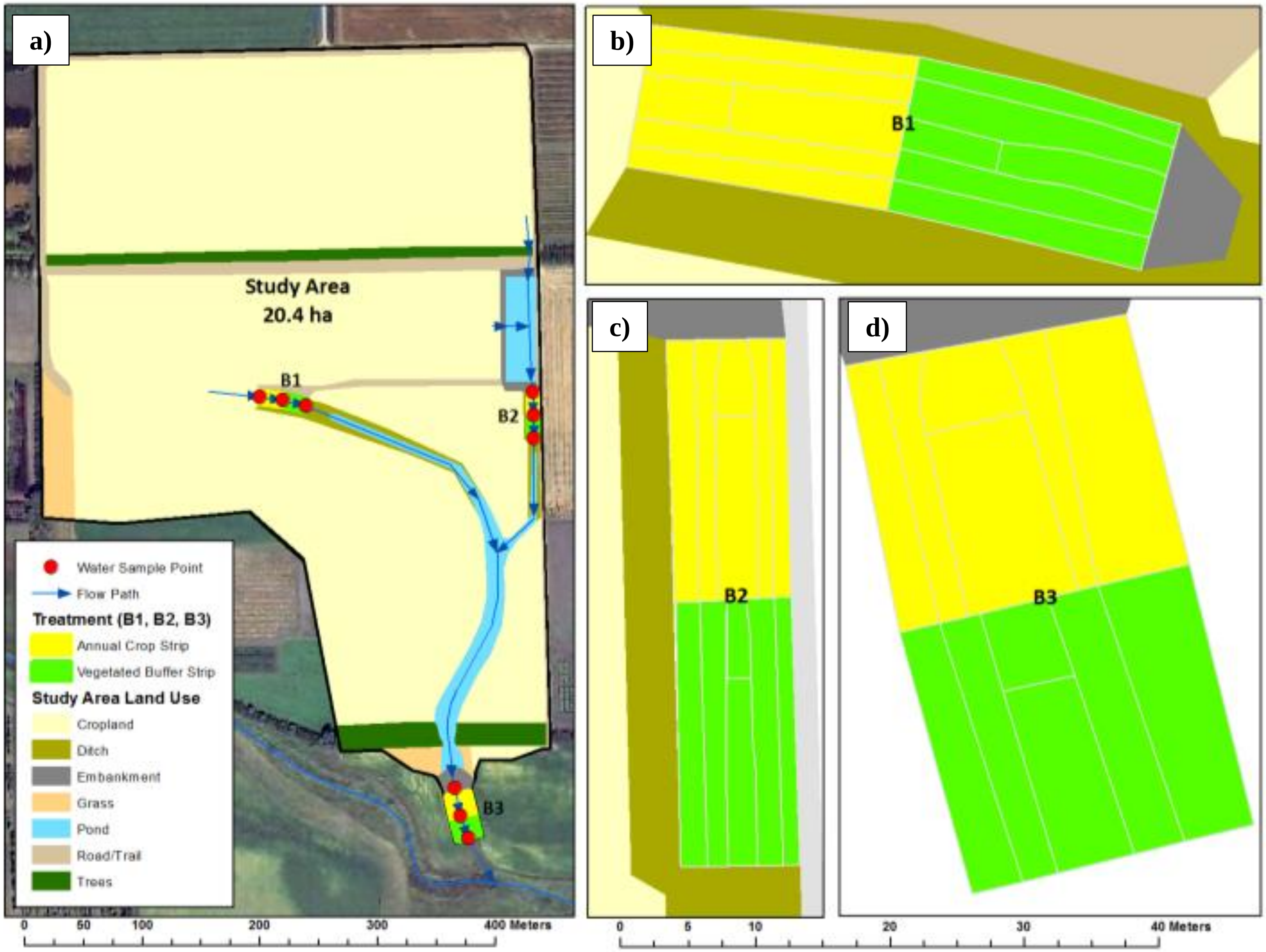

Figure 2.2. Study area land use and site layout (a) with locations of site B1 (b), site B2 (c), and site B3 (d).

Table 2.1. Monthly average climate data for Morden, Manitoba, Canada (1981 – 2010)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Rainfall (mm)	0.4	2.4	8.6	22	56.4	93	79	71	44	43	4.7	2.2	427
Snowfall (cm)	19	17	14	13	2	0	0	0	0	7	26	18	116
Precipitation (mm)	19	19	23	35	58.4	93	79	71	45	50	30	20	541
Average Snow Depth (cm)	11	12	8	1	0	0	0	0	0	0	5	9	4

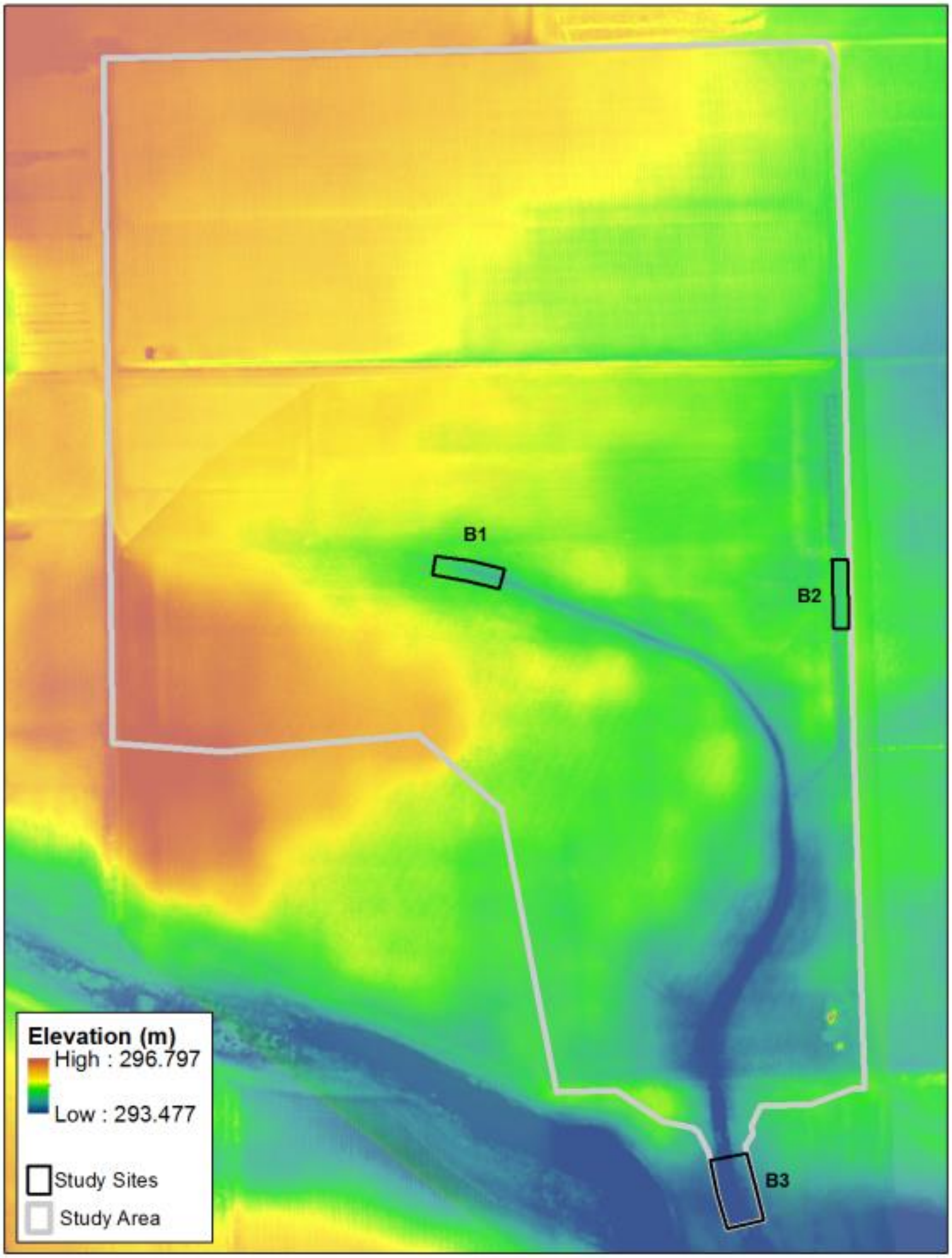

Figure 2.3. Study area elevation. Gray outline indicates the 20 ha drainage area for the site. Sites B1, B2, and B3 are indicated by the black outlined polygons.

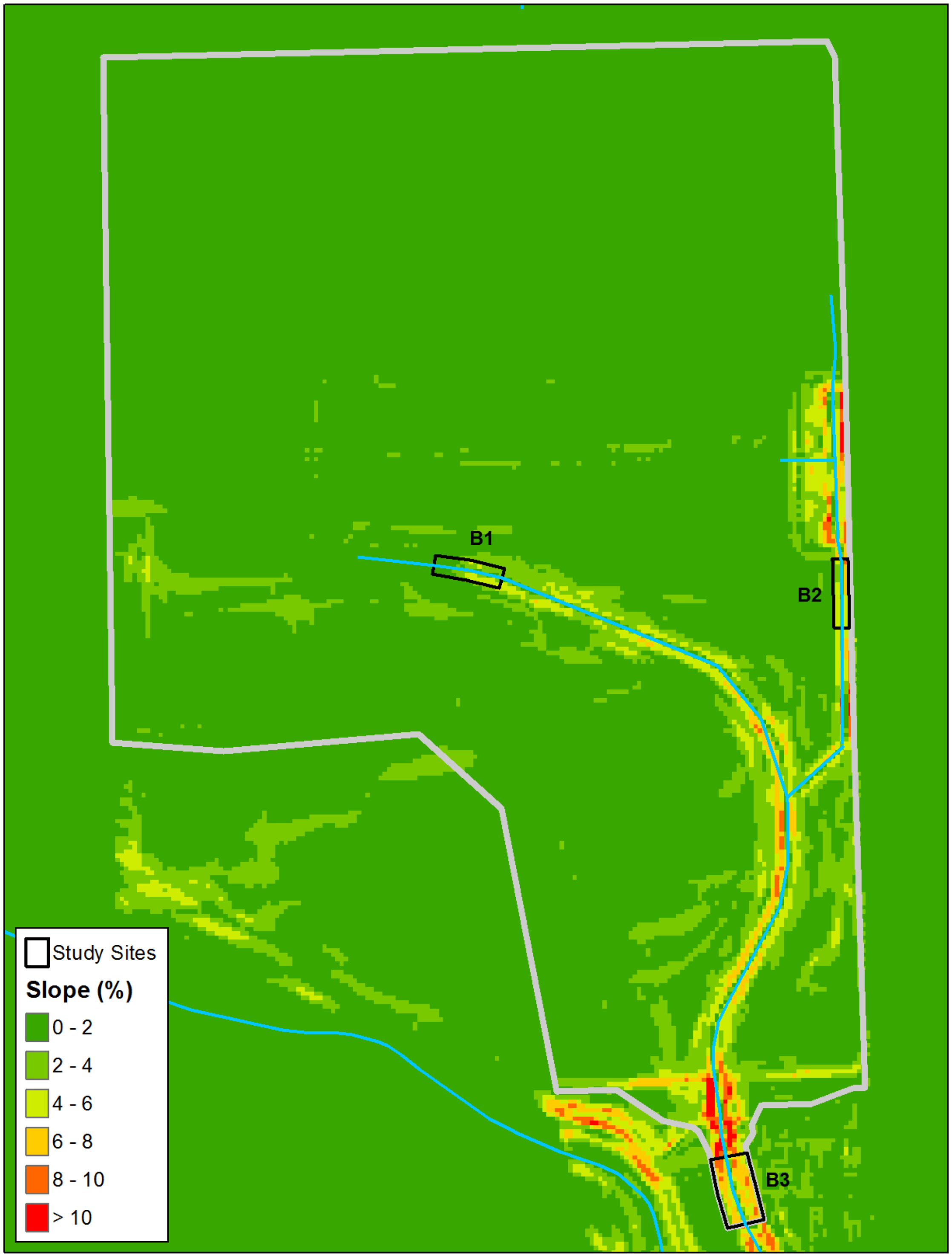

Figure 2.4. Study area slope. Gray outline indicates the 20 ha drainage area for the site. Sites B1, B2, and B3 are indicated by the black outlined polygons.

Figure 2.5. Study area soils. Soil series include Hochfeld (HHF), Edenburg (EBG), Eigenhof (EGF), Rosengart (RSG), Rignold (RGD), Graysville (GYV), Neuenberg (NBG), and Chortitz (CTZ). Background photo from May 2018.

2.2.2. Vegetated buffer and control strip establishment

Each site (B1, B2, and B3) includes a treatment pair, consisting of the control strip (C1, C2, and C3), seeded annually to an annual crop, and the perennial VBS (VBS1, VBS2, and VBS3). Site B1 was located in a natural swale that collected and concentrated flow from the adjacent field (Figure 2.6a). The other VBS sites were established as part of a larger initiative that included the construction of two retention ponds and drainage channel enhancements in October of 2014. This included the construction of a retention pond with a deepened drainage channel where site B2 was established (Figure 2.6b). Another retention pond was constructed to receive the runoff from sites B1 and B2 and also act as source water during overflow and releases to site B3 (Figure 2.6c). The swales and drainage channels were all bare soil in the spring of 2015 prior to VBS establishment.

All plots were 20 m in length parallel to the flow direction with the control strip plots located immediately upstream of the VBS plots (Figure 2.7). The VBS were seeded to a mixture of grass and forbs in the spring of 2015 using a Great Plains drill (Figure 2.8). At the time of VBS seeding, moisture conditions were adequate for establishment (Figure 2.9). Despite the dry growing season of 2015, the VBS plot vegetation became reasonably well established by late July (Figures 2.10, 2.11, and 2.12). The control strip plots were seeded annually in the spring to the same crop as the adjacent field using the same Great Plains drill that was used for seeding the VBS plots. In 2016, plots C1 and C2 were seeded to canola, while plot C3 was soybean. In 2017 all control strip plots were seeded to spring wheat. The control strip plots were managed identically to the adjacent cropped field (i.e. uniform field management). They were fertilized at the same rate, seeded to the same crop, harvested at the same time and received the same operations for pest management and tillage.

Figure 2.6. Site B1 prior to VBS establishment May, 2015 (a). Site B2 prior to VBS establishment, April, 2015 (b). Site B3 prior to VBS establishment, October 2014 (c).

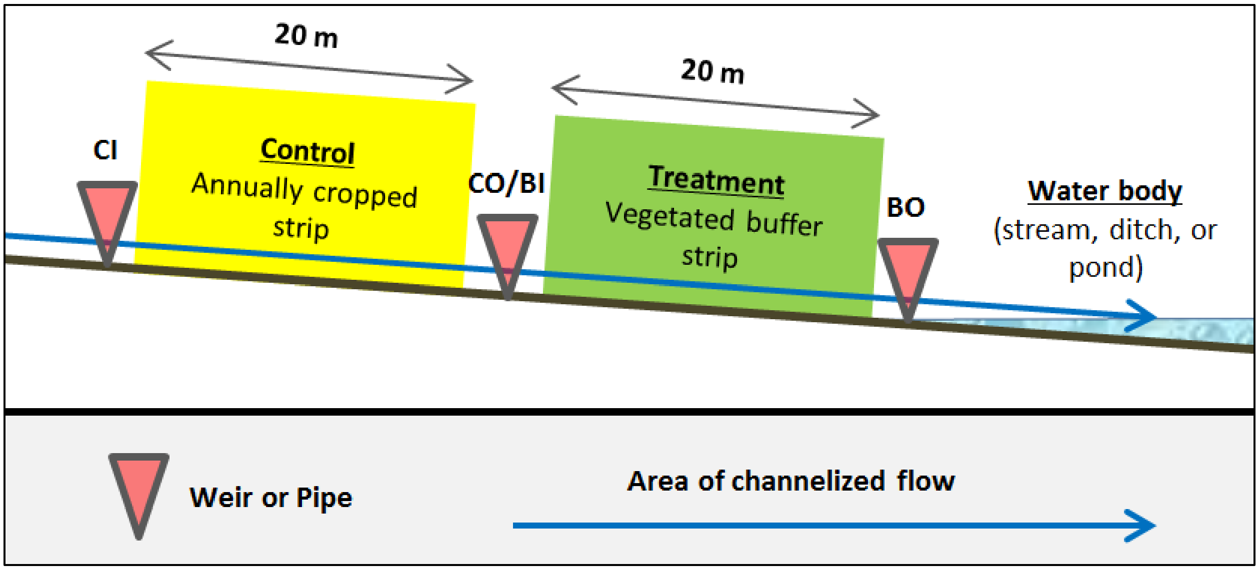

Figure 2.7. Schematic of the study layout. 20 m control (annual crop) strip upstream of a 20 m vegetated buffer strip

Figure 2.8. Great Plains Drill used for seeding of grasses and forbs and annual crop treatments

Figure 2.9. Site B3 just after seeding of a grass and forb mixture in the VBS treatment, April 30, 2015

Figure 2.10. Site B1 during VBS establishment, July 2015

Figure 2.11. Site B2 during VBS establishment, July 2015

Figure 2.12. Site B3 during VBS establishment, July 2015

2.2.3. Water monitoring locations

Water monitoring locations were established at the inflow and outflow of each of the plots (i.e. three control strips and three VBS plots) (Table 2.2 and Figure 2.13). To facilitate the measurement of runoff and the collection of water samples, weirs were constructed at the inflow and outflow of each treatment in the fall of 2015, unless the location was equipped with a pipe inlet or outlet as part of the retention ponds (Figure 2.14 and 2.15). Sites with pipe inlets or outlets included outflow from B1 and B3 and inflow to B2 and B3.

Overflow and release water from retention ponds was directed through small berms equipped with inline water control structures (AgriDrain Corporation, Adair, IA, USA) into sites B2 and B3. The inline water control structures are equipped with logs to control water levels in the upstream retention ponds and can be removed to facilitate the release of water into the downstream treatment sites (Figure 2.16 and 2.17).

Table 2.2. Sites, plots, and water monitoring locations

Site ID	**B1**	**B2**	**B3**
VBS Plot ID	VBS1	VBS2	VBS3
Control Strip Plot ID	C1	C2	C3
Control Strip Inflow Monitoring Location	C1I	C2I	C3I
Control Strip Outflow Monitoring Location	B1I	B2I	B3I
VBS Inflow Monitoring Location	B1I	B2I	B3I
VBS Outflow Monitoring Location	B1O	B2O	B3O

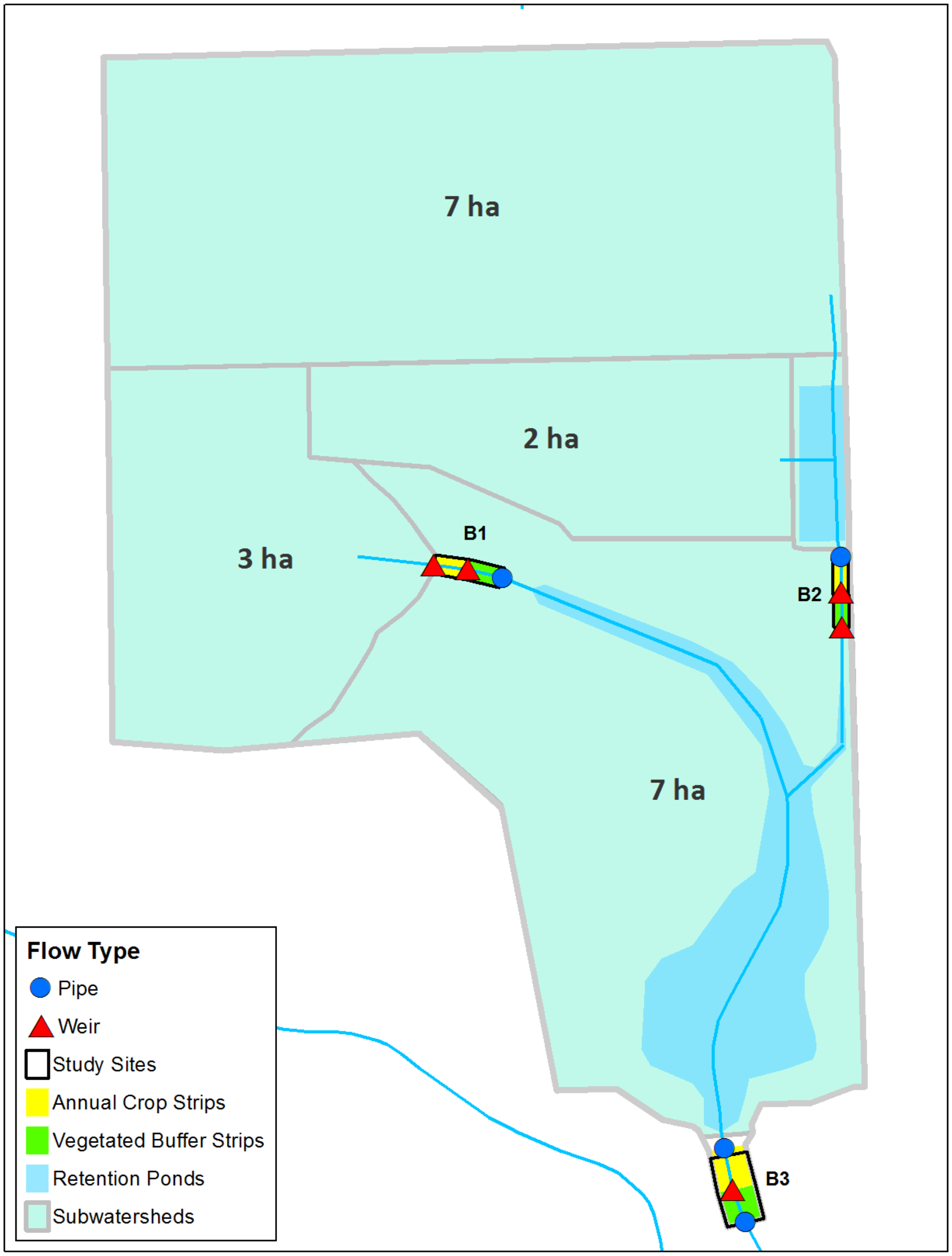

Figure 2.13. Study area water collection locations showing drainage areas and the location of weirs and pipe outlets. The objective of the weirs and pipes was to monitor water and P going into and out of the control strip and VBS plots, where the middle location represents the outflow of the former and the inflow of the latter

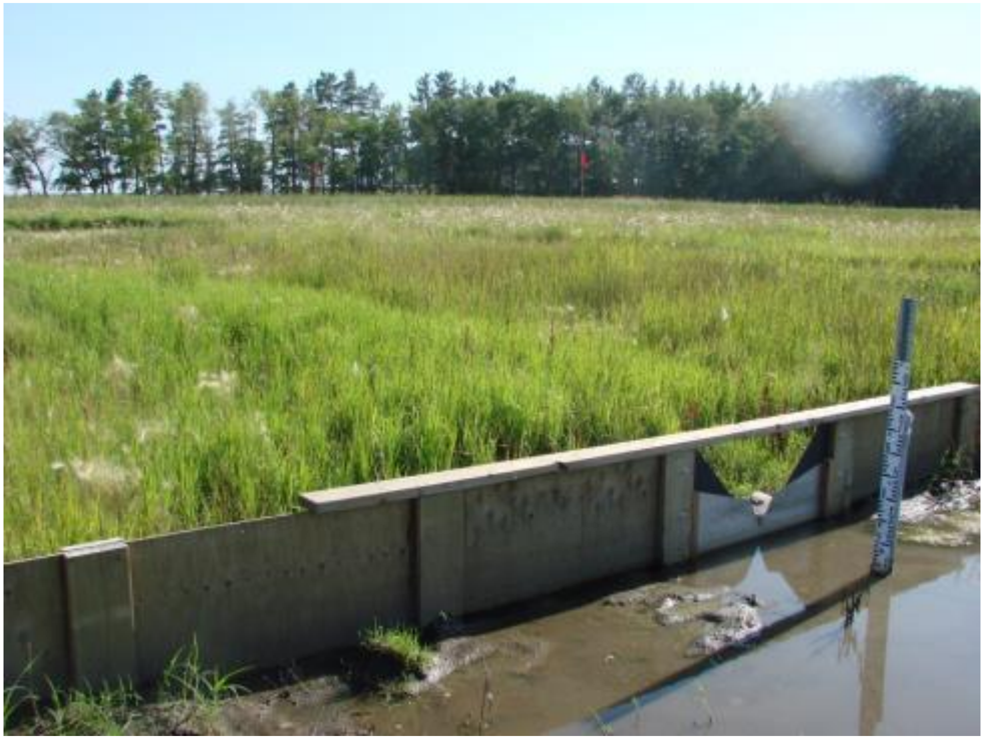

Figure 2.14. V-notch weir at Site B3, August, 2016

Figure 2.15. Outlet pipe through berm at site B1, August 2016

Figure 2.16. Agridrain control structure at retention pond outlet and inlet into site B3, May 2015

Figure 2.17. Inside of Agridrain control structure at retention pond, inlet into site B3, May 2015

2.2.4. Water level recording and sample collection

Each site (B1, B2, and B3) includes a treatment pair, consisting of the control strip (C1, C2, and C3), seeded annually to an annual crop, and the perennial VBS (VBS1, VBS2, and VBS3). The control strip inflow (CI) sites include C1I, C2I, and C3I monitoring locations (Figure 2.18, Table 2.2). The control strip outflow points also serve as the VBS or buffer inflow (BI) sites and include B1I, B2I, and B3I monitoring locations. The outflow from the VBS, or buffer outflow (BO) sites include B1O, B2O, and B3O monitoring locations. All nine monitoring locations were equipped with level loggers (Odyssey Capacitance Water Level Logger, Christchurch, NZ) to record continuous water levels every 15 minutes. The free flowing monitoring locations (i.e. those not downstream of a retention pond), including C1I, B1I, and B1O, were equipped with automated samplers (Hach Sigma 900 Portable Sampler, Loveland, CO, USA) set to collect 1L water samples every 6 hours. Automated water samples were augmented by grab samples taken frequently at all sites during all runoff events, multiple times per day, wherever possible during longer duration runoff events that lasted more than a few hours. Grab samples were especially critical during snowmelt when automated samplers were not deployed due to the risk of freezing. Water samples were collected during four types of runoff events: two natural and two artificial. Natural runoff events were those derived from either snowmelt or rainfall. To gather additional data, “artificial events” were induced during dry periods (fall 2015, spring 2016, and fall 2016) by pumping water from a nearby irrigation reservoir directly into C1I and into the retention pond upstream of C2I. A final type of event, termed “pond outflow”, occurred when there was sufficient natural runoff water in either of the two retention ponds that produced overflow into C2I or C3I.

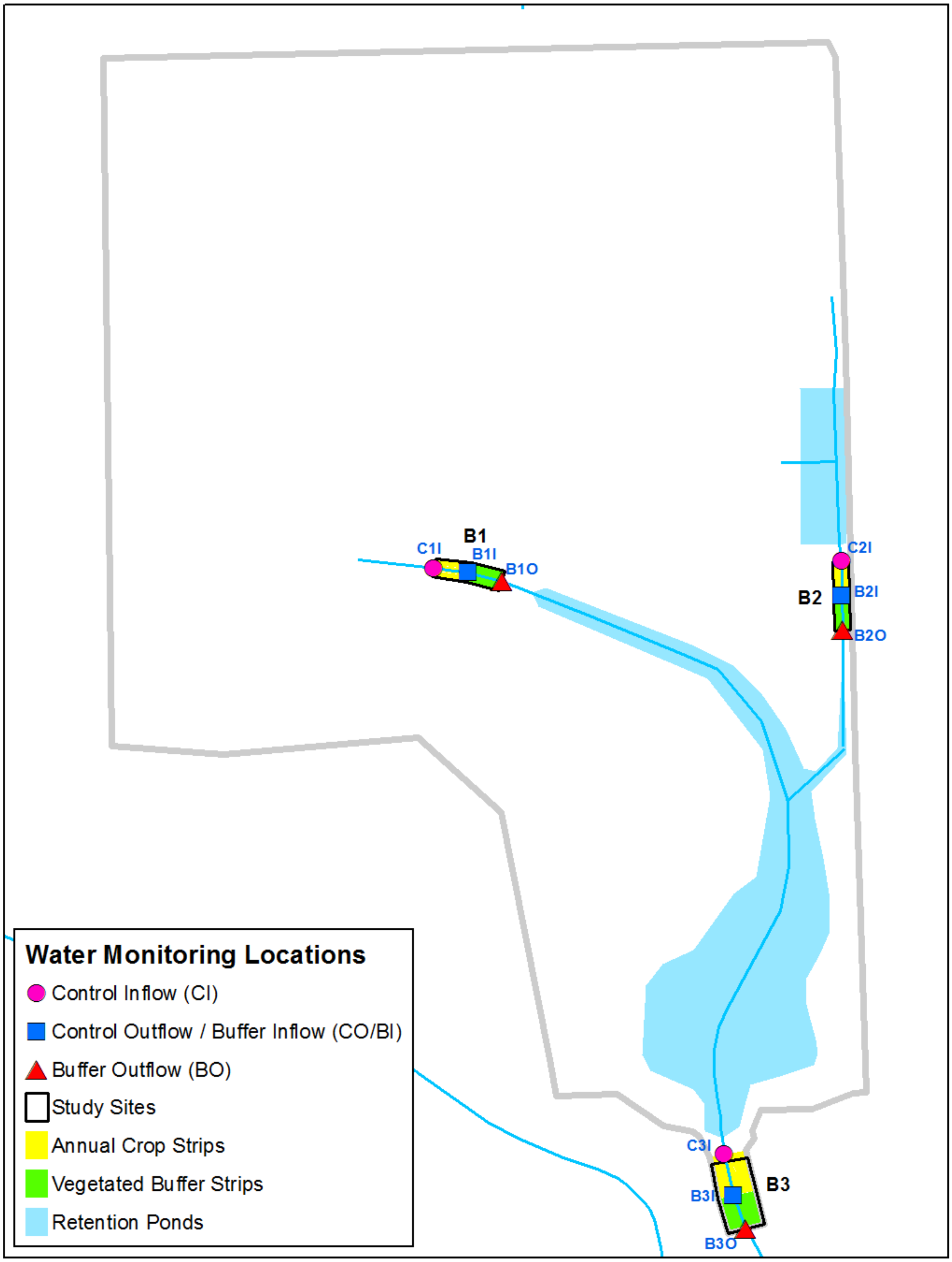

Figure 2.18. Water level and sample collection sites

2.2.5. Water sample analysis

A portion of the water samples (250 mL) were filtered through 0.7 µm pre-ashed glass fiber filters and preserved by freezing for later analysis. Samples were usually filtered and frozen within 24 hours of collection. However, some samples from autosamplers were not retrieved and filtered until about 48 hours after they were collected. Frozen samples were sent to the Agriculture and Agri-Food Canada (AAFC) Hydrology Laboratory in Brandon, MB, where they were later thawed for analysis. The filtered samples were used for determination of total dissolved P (TDP) concentration while unfiltered samples were used to measure total P (TP) concentration using standard laboratory techniques for water and wastewater described in Rice et al. (2012). The method included the digestion of the samples by combining 10 mL of sample with 3.2 mL of potassium persulfate and then placing them in an autoclave for 30 minutes at 103 kPa. The digested samples were then analyzed for P as the orthophosphate ion using a Smartchem Discrete Wet Chemistry Analyzer (SMARTCHEM® 170, Westco Scientific, Brookfield, CT, USA) using EPA method 365.1 (O'Dell, 1993).

For calculation of total suspended solids (TSS), filters were dried by heating in an oven at 40°C for one hour. The mass of the filtrate, or TSS, was then determined by subtracting the original mass of the ashed filter from the mass of the dried filter with the filtrate, and dividing by the volume of filtered water. TSS is the material in the sample that is not dissolved (i.e. particles > 0.7 µm) including sediment and debris such as suspended plant material.

2.2.6. Flow data and runoff volumes

Due to factors such as weir submergence and flow meter limitations for low flow conditions, flow rates at the water monitoring sites could not be accurately derived from the water level data. Alternatively, total runoff volume for an event was estimated by comparing the initial volume of a downstream pond to the volume after the event (i.e. the change in volume). Although this method does not account for all hydrological processes that would occur during the events such as losses through evaporation and seepage and additional water from direct precipitation, these are likely to be negligible due to the short duration of these events and the frequency of pond volume calculations (i.e. daily at a minimum). The water yield for the study watersheds in mm was then calculated by taking the total event runoff volume (m^3) divided by the drainage area for the pond (m^2) and multiplied by 1,000 to convert from m to mm, expressed as:

Eqn. 2.1. EWY = ERV/PDA*1,000

where,

EWY = event water yield (mm)

ERV = event runoff volume (m^3)

PDA = pond drainage area (m^2).

2.2.7. Event mean concentration and load calculation

The event mean concentration (EMC) for the different parameters (TDP, TP, and TSS) were determined by calculating the mean of all sample concentrations for a specific event for a given site. Site event volume (m^3) was calculated by multiplying the event water yield (mm) by the site contributing drainage area (m^2) and divided by 1,000 to convert from mm to m.

Eqn. 2.2. SEV = EWY*SDA/1,000

where,

SEV = site event volume (m^3)

EWY = event water yield (mm)

SDA = site contributing drainage area (m^2).

Site event load (g) was calculated for a given event and site by multiplying the event mean concentration (mg/L) of the parameter by site event volume (m^3), expressed as:

Eqn. 2.3. SEL = EMC*SEV

where,

SEL = site event load (g)

EMC = event mean concentration (mg/L)

SEV = site event volume (m^3).

2.3. Results

2.3.1. Event descriptions

Over the duration of this study between the fall of 2015 and spring of 2017, 22 events occurred where at least one water sample was collected at each of the three monitoring locations (CI, CO/BI, and BO) for each site (Table 2.3). A total of 355 water samples were collected. Most events, with the exception of two (Events 16.1 and 16.7; where the first number is the year and the second number is the event within that year), had multiple samples collected per monitoring location per event. Event mean concentrations were calculated for each monitoring location that had multiple samples during an event. Event 17.3 in spring of 2017 had the most samples collected with 18 samples per monitoring location at B3. The spring snowmelt event of 2016 (Event 16.1) was a natural runoff event (upstream of a retention pond) while the other spring events in 2017 (Events 17.2 and 17.3) were both pond outflow events (i.e. downstream of retention ponds). There were seven natural rainfall driven events, all in 2016. There were 10 artificial events that were conducted during prolonged dry periods, with four of these in the spring (2016) and six in the fall (2015 and 2016). There was sufficient natural runoff to fill and release from ponds through the treatment sites (B2 and B3) for four events, two in the growing season of 2016 and two during the snowmelt of 2017.

During some small events, the change in water level in the receiving ponds was negligible resulting in runoff volume estimates that were very low or zero. Most of these extremely small events (<10 m^3 runoff) were either artificial events where a minimal amount of water was pumped through the sites (Events 16.3 and 16.4), a small pond outflow (Event 17.2), due to low rainfall levels (<15mm) (Event 16.10), or occurred after prolonged dry periods. Extended dry periods, including the spring and early growing season of 2016, were observed where the precipitation during this time generated very little runoff (Events 16.7, 16.9, and 16.10). The largest event (Event 17.3) generated an estimated volume of 913 m^3. This event was the result of the substantial runoff from the melting of the large snowpack in the spring of 2017 that filled and flowed through the southern retention pond into site B3 (Figure 2.19). Site conditions changed dramatically as the seasons progressed from snowmelt into the other seasons. The vegetation in the VBS plots were flattened and often covered by snow and ice while the control strip plots were mainly bare ground with some crop residue cover during snowmelt conditions (Figure 2.20a). Conversely, the VBS and control strip plots contained dense stands of vegetation during the summer months (Figure 2.20b).

Figure 2.19. Pond upstream of site B3 at full capacity April, 2017

Table 2.3. Flow events from fall 2015 to spring 2017

Event ID	Season	Event Type	Event Site	Plots	Start Date	End Date	Precipitation (mm)	Site Event Volume (m^3)	Total Samples For All Water Sample Sites Involved	Minimum Sample Number Per Water Sample Site (CI; CO/BI; or BO)
5.1	fall	artificial	B2	C2 /VBS2	2015-10-28	2015-10-29	0.0	62	19	5
16.1	spring	snowmelt	B1	C1/VBS1	2016-03-06	2016-03-16	13.3	55	3	1
16.3	spring	artificial	B1	C1/VBS1	2016-04-22	2016-04-26	5.8	7	33	11
16.4	spring	artificial	B3	C3/VBS3	2016-04-27	2016-04-27	0.0	4	12	3
16.5	spring	artificial	B2	C2 /VBS2	2016-04-28	2016-04-28	0.0	56	18	6
16.6	spring	artificial	B3	C3/VBS3	2016-05-03	2016-05-03	0.0	32	6	2
16.7	growing	rain	B1	C1/VBS1	2016-05-22	2016-05-26	46.7	0	8	1
16.9	growing	rain	B1	C1/VBS1	2016-06-10	2016-06-10	22.8	2	6	2
16.10	growing	rain	B1	C1/VBS1	2016-06-12	2016-06-12	14.7	4	6	2
16.11	growing	rain	B1	C1/VBS1	2016-06-17	2016-06-19	44.0	169	14	5
16.14	growing	rain	B1	C1/VBS1	2016-07-11	2016-07-12	31.5	79	13	5
16.15	growing	rain	B1	C1/VBS1	2016-07-19	2016-07-21	26.3	23	7	2
16.16	growing	pond outflow	B3	C3/VBS3	2016-07-28	2016-07-28	0.0	43	17	5
16.17	growing	rain	B1	C1/VBS1	2016-08-03	2016-08-04	38.3	81	8	2
16.18	growing	pond outflow	B3	C3/VBS3	2016-08-09	2016-08-12	2.7	455	21	7
16.20	fall	artificial	B2	C2 /VBS2	2016-10-20	2016-10-21	0.0	79	20	6
16.21	fall	artificial	B1	C1/VBS1	2016-10-24	2016-10-25	0.0	74	15	5
16.22	fall	artificial	B1	C1/VBS1	2016-10-25	2016-10-26	5.4	155	22	11
16.23	fall	artificial	B3	C3/VBS3	2016-10-27	2016-10-28	0.0	343	14	4
16.24	fall	artificial	B3	C3/VBS3	2016-10-31	2016-10-31	11.9	32	6	2
17.2	spring	pond outflow	B2	C2 /VBS2	2017-03-28	2017-04-05	0.2	8	33	11
17.3	spring	pond outflow	B3	C3/VBS3	2017-04-12	2017-04-28	7.9	913	54	18

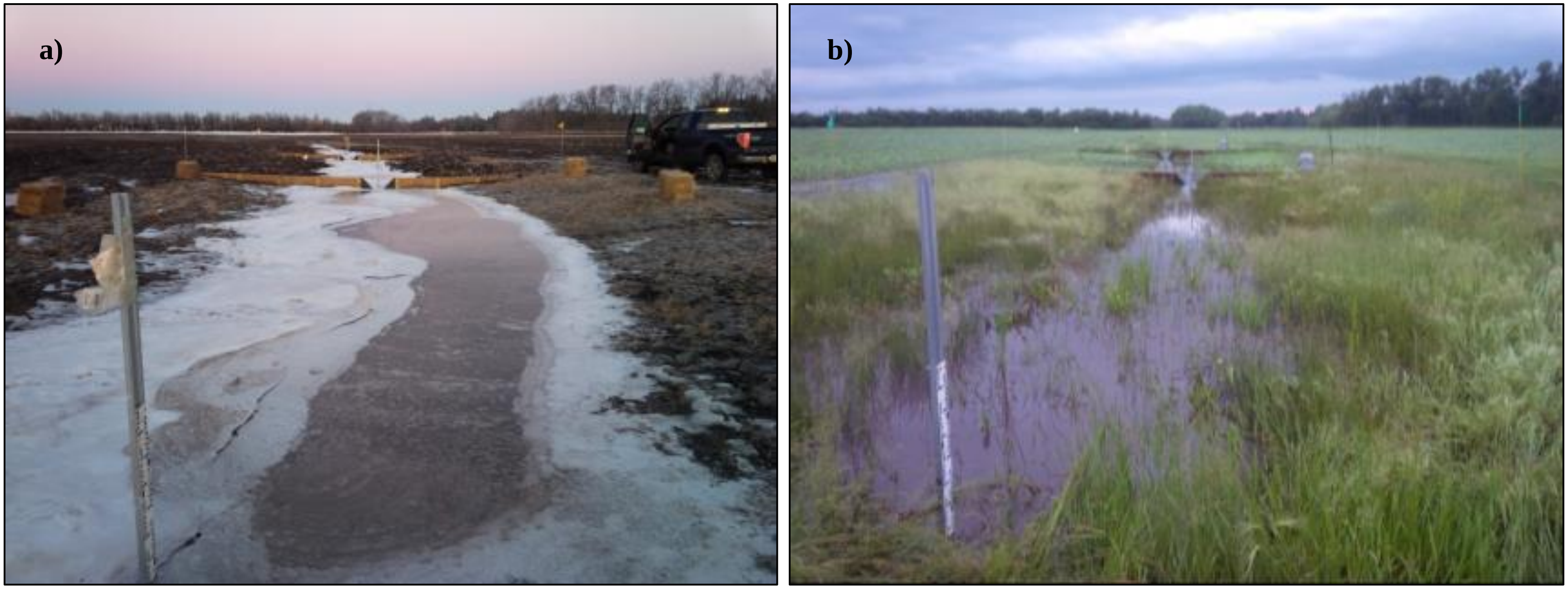

Figure 2.20. Site B1 (C1 and VBS1) showing water monitoring locations C1I, B1I, and B1O during events in March 2016 (a) and June 2016 (b).

2.3.2. Vegetated buffer strip performance for phosphorus and suspended solid concentration reduction

The summary statistics for all the TDP, TP, and TSS concentration data for all events by the three sample location types [i.e. control strip inflow (CI); control strip outflow / VBS inflow (CO/BI); VBS outflow (BO)] are presented in Table 2.4. Two samples at CO/BI locations had damaged or missing filters and the TSS could not be measured. For TDP, the highest mean concentrations were found at the CI locations followed by the CO/BI locations and the BO locations (221.8 µg/L, 195.9 µg/L, and 178.3 µg/L respectively). Similarly, the highest mean TP concentrations were found at the CI locations followed by the CO/BI locations and then the BO locations (272.0 µg/L, 257.1 µg/L, and 227.7 µg/L respectively). The TP data by sample location type are presented in box and whisker plots in Figure 2.21. Although the mean TP was lower at the VBS outflow, or BO, locations, according to Kruskal-Wallis One-way ANOVA on Ranks comparison of medians for non-normal data, there was no statistical difference ($P=0.807$). Similarly, there was no statistical difference in medians of TDP at the VBS outflow locations ($P=0.996$) compared to the inflow locations.

Mean concentrations for TSS did not follow the same pattern as TDP and TP, with the highest mean TSS values found at the CO/BI locations, followed by the CI locations, then the BO locations (53.1 mg/L, 43.2 mg/L, and 37.3 mg/L respectively).

Table 2.4. Summary statistics for phosphorus (total dissolved (TDP) and total (TP)) and suspended solids (TSS) concentration in water samples by sample location type

	TDP (μg/L)			TP (μg/L)			TSS (mg/L)		
	CI	**CO/BI**	**BO**	**CI**	**CO/BI**	**BO**	**CI**	**CO/BI**	**BO**
Mean	221.8	195.9	178.3	272	257.1	227.7	43.2	53.1	37.3
Std. Dev.	299.3	243.6	200.9	342.1	275.6	230.4	99.2	92	67.4
Samples (n)	118	115	122	118	115	122	118	113	122
Min.	11.3	12.2	15	22.7	23	16.7	0	0.8	0
Max.	1708	1783.2	1239.8	2201.8	2073.8	1530.6	694	550.4	428

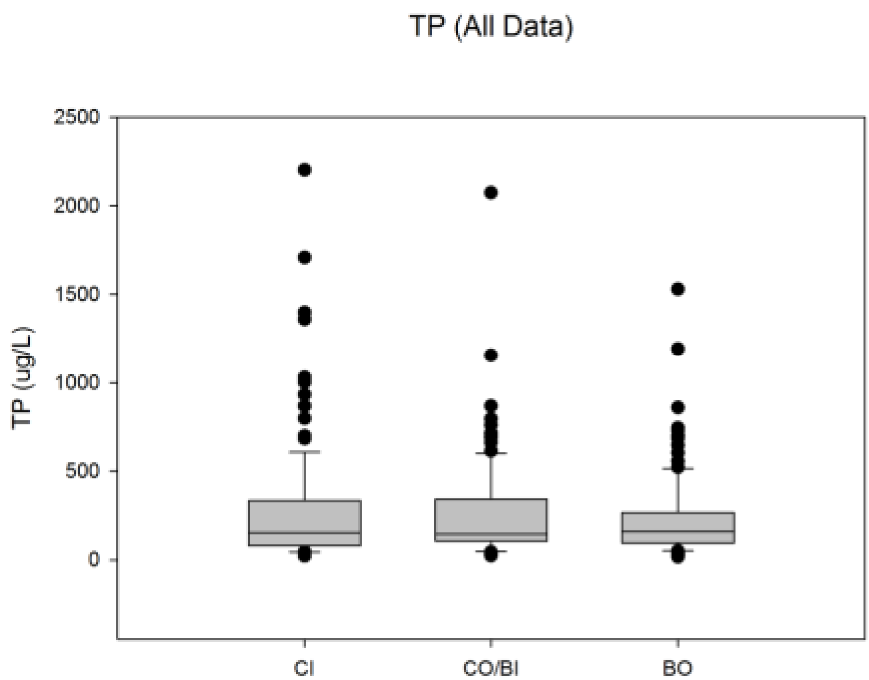

Figure 2.21. Box plot of TP concentrations for all data by location type

The mean TDP:TP ratio for all data was 0.71. Figure 2.22 summarizes the TDP:TP ratios by water sample location type. The control strip outflow/VBS inflow (CO/BI) locations had a slightly lower mean TDP:TP ratio than the VBS outflow (BO) and control strip inflow (CI) locations (0.68, 0.72, and 0.73 respectively).

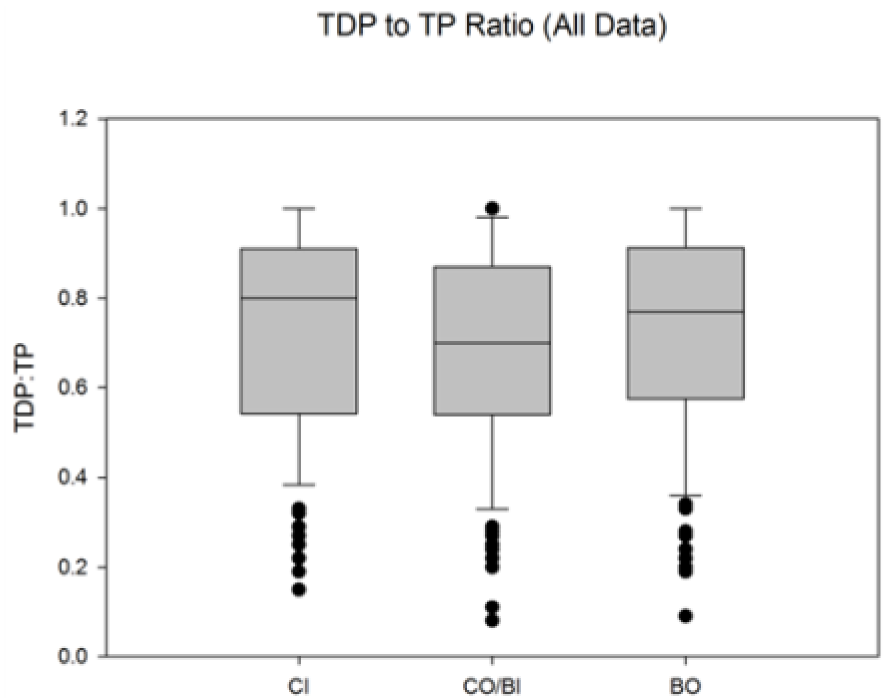

Figure 2.22. Box plot of TDP:TP ratio by location type

By comparing the control strip and VBS inflow and outflow location mean concentrations, a mean percent reduction in concentration can be calculated using the following formula:

Eqn. 2.4. PR = (IC – OC)/IC *100

where,

PR = percent reduction (%)

IC = inflow concentration (µg/L)

OC = outflow concentration (µg/L).

Percent reduction in mean concentrations for control strip and VBS sites for TDP, TP, and TSS are shown in Table 2.5. Mean TDP reductions were similar for control strip and VBS sites (12% and 9% respectively). The VBS sites performed slightly better than control strips for mean

TP concentration reduction (11% and 5%, respectively). For TSS concentrations, the VBS performed substantially better than the control strips. The VBS reduced mean TSS concentrations by 30% while the control strips increased mean TSS concentrations by 23%. Although there is a substantial reduction in mean TSS concentration leaving the VBS sites, the Mann-Whitney Rank Sum Test for non-normal data shows no statistical difference in the median VBS inflow and outflow TSS concentrations (P=0.193).

Table 2.5. Mean total dissolved phosphorus (TDP), total phosphorus (TP), and total suspended solids (TSS) concentration reduction for control strip and VBS treatments

TDP		TP		TSS	
Control Strip	VBS	Control Strip	VBS	Control Strip	VBS
12%	9%	5%	11%	-23%	30%

The TP, TDP, and TSS concentration data for the three different sites (B1, B2, and B3) are presented in Table 2.6 and Figure 2.23. The TP concentrations were substantially higher at site B1 (337.5 – 434.6 µg/L) than sites B2 and B3 (138.0 – 203.4 µg/L). Similar patterns were evident for TDP and TSS where site B2 and B3 concentrations were substantially lower. The lower TP concentrations at B2 and B3 sites was due to the fact that most of the events were artificially induced using water from a nearby reservoir that was low in TP, TDP and TSS and that these sites are located downstream of retention ponds. These ponds and similar water retention structures have been reported to lower P concentrations in this region, especially particulate P (Tiessen et al., 2011).

Although none of the sites reduced the mean concentration of TP statistically (i.e. no plots have a statistical difference between VBS inflow and outflow TP concentrations), site B2 (plot VBS2) numerically reduces mean TP concentrations by the largest amount (a 23% reduction).

An assessment of the performance of the VBS sites by each event revealed considerable variability. Event mean TP concentrations by location type (CI, CO/BI, and BO) and VBS performance for each event expressed as percent TP concentration reduction are presented in Figure 2.24. Negative reductions indicate an increase in event mean TP concentration. In 14 out of the 22 events, or 64%, the VBS treatment resulted in a reduction in event mean TP concentration.

Table 2.6. Mean total phosphorus (TP), total dissolved phosphorus (TDP) and total suspended solid (TSS) concentration by site and water monitoring location type

	B1			B2			B3		
	CI	**CO/BI**	**BO**	**CI**	**CO/BI**	**BO**	**CI**	**CO/BI**	**BO**
Samples	49	39	47	28	31	31	41	45	44
Mean TP (µg/L)	405.9	434.6	337.5	138.0	161.5	153.1	203.4	169.1	163.1
Mean TDP (µg/L)	354.9	368.9	290.4	119.6	130.7	123.4	132.5	90.9	97.1
Mean TSS (mg/L)	75.4	97.7	59.7	12.6	13.3	11.9	25.6	43.9	31.3

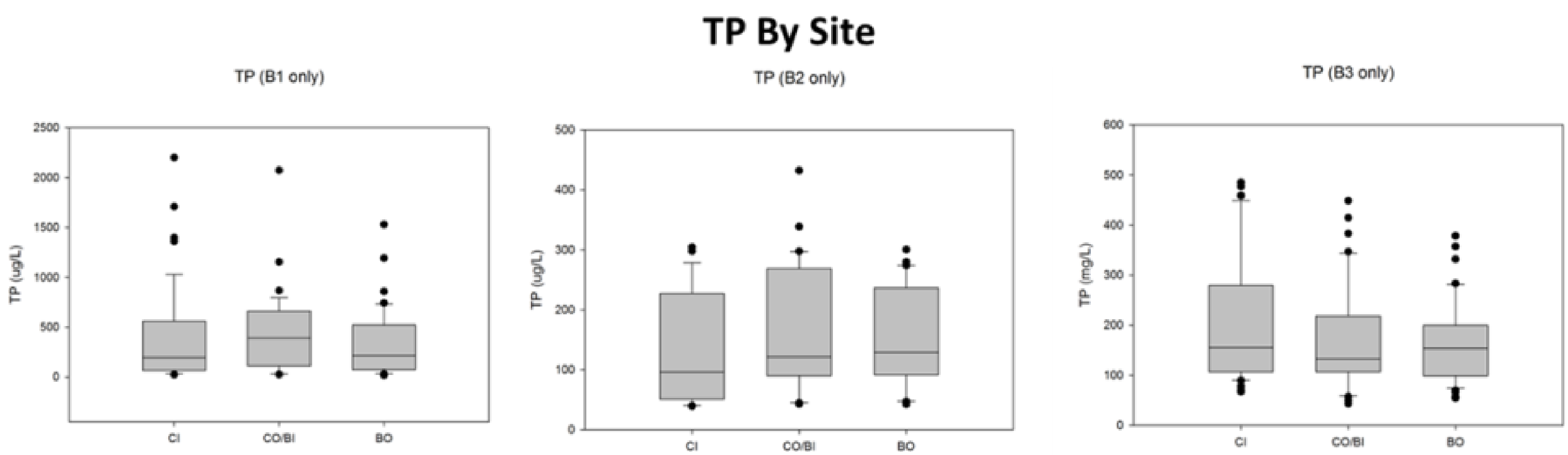

Figure 2.23. Total phosphorus (TP) concentration data for the three sites (B1, B2, and B3)

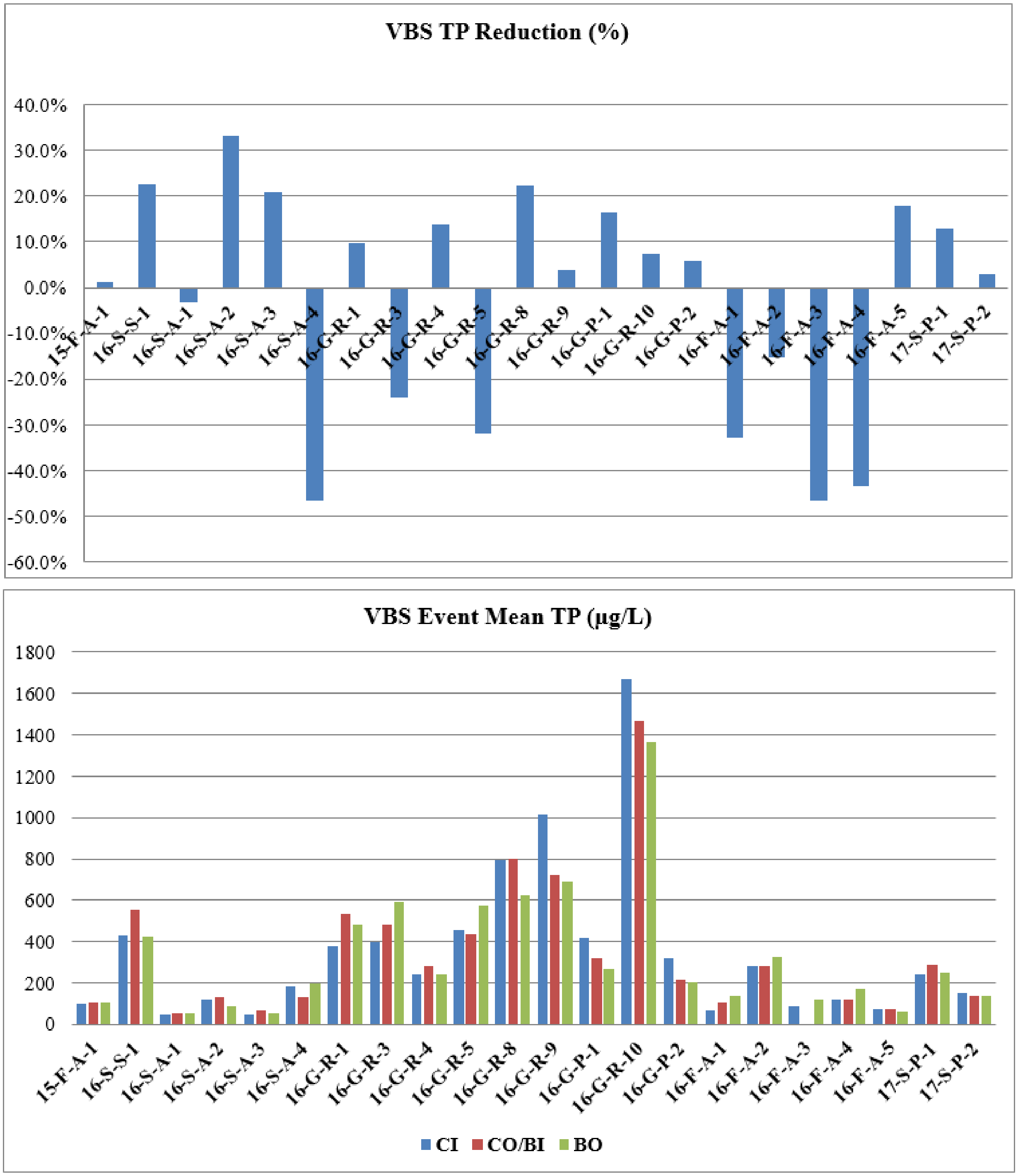

Figure 2.24. Event mean VBS TP reductions in % (top graph) and event mean total phosphorus (TP) concentrations (bottom graph)

2.3.3. Vegetated buffer strip performance for phosphorus load reduction

Load reduction was calculated by subtracting the outflow load (g) from the inflow load (g). Due to aforementioned factors, actual flows at the water sample points could not be measured and therefore actual loads could not be calculated. For the purpose of this study, flow volumes were assumed to be the same (constant) at the VBS inflow and outflow sites (i.e. no flow reduction through a VBS) and the load reductions were based entirely on the estimated event flow volume and the change in TP concentrations as the runoff passed through the VBS. The TP load reductions by event are presented in Figure 2.25. Negative load reductions indicate an increase in TP load passing through the VBS.

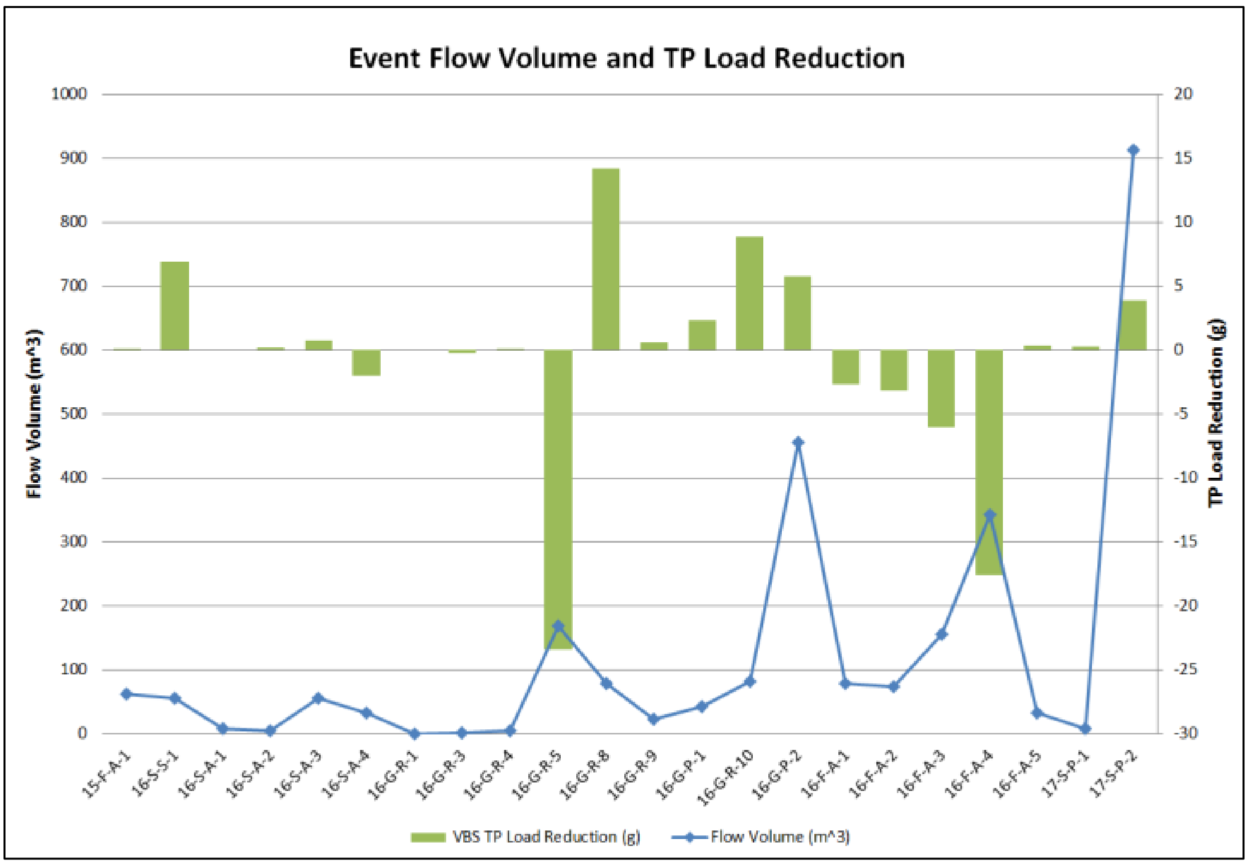

Figure 2.25. Total phosphorus (TP) load reduction and flow volume by event

2.4. Factors affecting vegetated buffer strip performance

2.4.1. Season

Most research on VBS performance for P retention has been done in warmer climates or in laboratory or field settings that are similar to the summer, or growing season, in cold regions. An important aspect of this study was to assess the performance of VBS in the different seasons that typically produce runoff, including spring, summer (or growing season), and fall periods. In cold climates, like the Canadian Prairies, the winter season usually produces little to no runoff, and precipitation, usually in the form of snow, accumulates. For the purpose of this study, the spring season is defined as the time period between when the snowmelt begins and when crops and perennial vegetation start to emerge and cover the ground with newly growing plant cover (i.e. March to May). The dominant form of runoff during the spring period is snowmelt. The summer or growing season, is the period when the vegetation – crops or perennial VBS vegetation – are actively growing (i.e. June to August). The fall is defined as the period when crops have ceased growing and are harvested for their grain, and when VBS vegetation has senesced and is no longer actively growing, but prior to the ground being frozen and snow accumulating (i.e. September to October). Runoff during the growing season and fall is almost entirely driven by rainfall.

The TP concentration data by location type for the three seasons (spring, summer/growing season, and fall) are presented in Figure 2.26. The VBS treatments have little effect on TP during the spring season but they numerically reduce TP concentrations during the growing season from a mean of 509.1 µg/L to a mean of 464.9 µg/L, or an 8.7% reduction. However, there is considerable variability in these data and the Mann-Whitney Rank Sum Test suggests there is no statistical difference in the median values (non-normal data distribution, median VBS inflow TP of 390.87 µg/L; median VBS outflow TP of 387.32 µg/L; P=0.576). In the fall period, mean TP concentrations numerically increase at the outlet of the VBS plots from 139.9.1 µg/L at the inflow location to a mean of 152.8 µg/L at the outflow location, a 9.2% increase. However, the there is no statistical difference in medians (Mann-Whitney Rank Sum Test, P=0.451).

2.4.2. Event type

The TP concentration data for artificial, natural runoff (rain and snowmelt), and pond outflow events are presented in Figure 2.27 and Table 2.7. During artificial events, mean VBS outflow TP concentrations increased by 10.0% (from 110.7 µg/L to 121.7 µg/L), while mean VBS outflow TP concentrations during natural events was reduced by 5.5 % (from 650.2 µg/L to 614.5 µg/L). During pond outflow events, mean VBS outflow TP concentrations were reduced by 9.8 % (from 216.1 µg/L to 195.1 µg/L). However, the Mann-Whitney Rank Sum Test suggests there was not a statistical difference between the VBS inflow and outflow median TP values for artificial, natural, or pond outflow events (P=0.719, P=0.779, P=0.450 respectively).

2.4.3. Event type and season

The TDP, TP, and TSS concentration data categorized by event type and season are presented in Table 2.8. The data were categorized into nine different groups based on event type (three types) and season (three seasons). This was reduced to six groups because there were no artificial events during the growing season, and no natural or pond outflow events in the fall. The only event type - seasons where event mean TDP was reduced in more than 50% of the events were artificial – spring (3/4 or 75% of events) and natural – spring (1/1 or 100% of events). The event type - seasons where event mean TP was reduced in more than 50% of the events were natural – spring (1/1 or 100% of events), natural – growing (5/7 or 71% of events), pond – spring (2/2 or 100% of events), and pond – growing (2/2 or 100% of events). The event type - seasons where event mean TSS was reduced in more than 50% of the events were only natural – growing (6/7 or 86% of events) and pond – growing (2/2 or 100% of events). Based on the total estimated flow volume and event mean concentrations for these event groups, TP load reductions were estimated to be negative (i.e. increased load) for artificial events in the spring and fall. The VBS TP load reductions were estimated to be highest in the pond - growing season events (8.1 g of TP retained), followed by natural – spring events (6.9 g of TP retained), pond – spring events (4.2 g of TP retained), and natural – growing (0.2 g of TP retained).

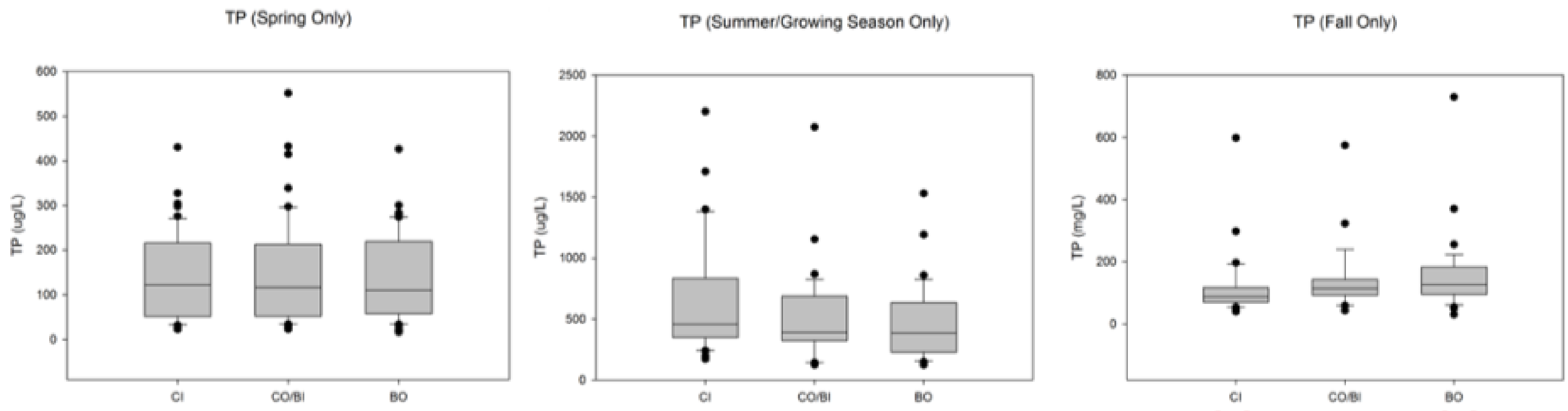

Figure 2.26. Box plots of total phosphorus (TP) concentration by location type and season

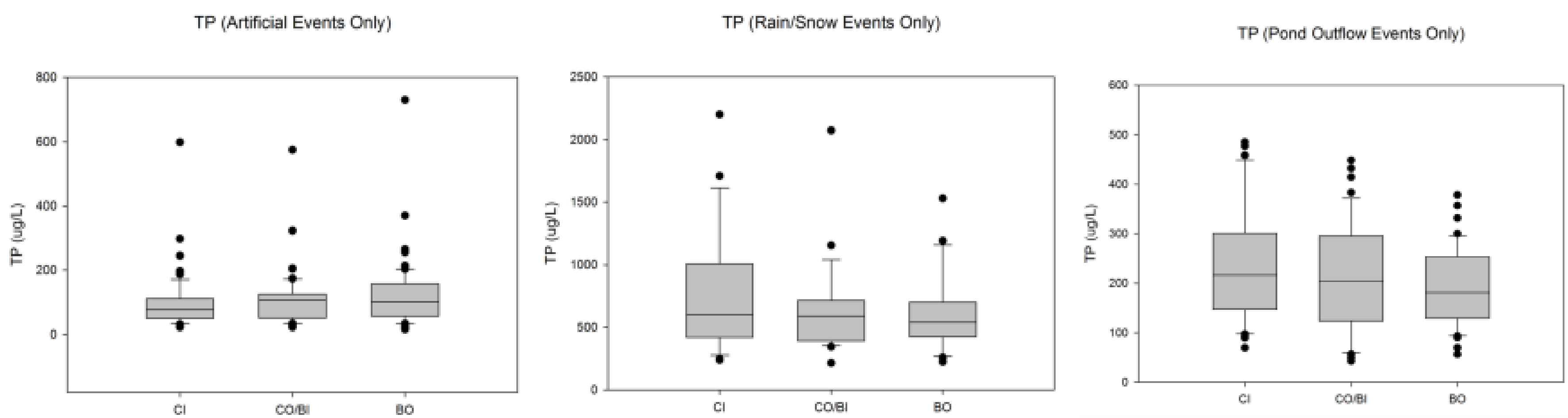

Figure 2.27. Boxplots of total phosphorus (TP) concentration for artificial, natural (rain/snowmelt), and pond outflow events

Table 2.7. Summary of total phosphorus (TP) concentrations for artificial, natural runoff, and pond outflow events

	Artificial			Natural			Pond Outflow		
	CI	CO/BI	BO	CI	CO/BI	BO	CI	CO/BI	BO
Samples (n)	55	50	60	22	23	20	41	42	42
Mean TP (µg/L)	97.4	110.7	121.7	775.5	650.2	614.5	235.9	216.1	195.1
Std. Deviation	87.8	86.9	105.6	509.2	373.6	232.4	114.3	112.5	80.1

Table 2.8. Summary of VBS performance by event type and season for TDP, TP, and TSS concentration reduction

	Artificial (Induced Runoff)			Natural (Overland Runoff)			Pond Outflow		
	Spring	Growing	Fall	Spring	Growing	Fall	Spring	Growing	Fall
Total Number of Events	4	0	6	1	7	0	2	2	0
Total Water Samples at VBS Inflow	24		26	1	22		29	13	
Events VBS Outflow TDP Reduced	3 (75%)		1 (17%)	1 (100%)	2 (29%)		1 (50%)	1 (50%)	
Events VBS Outflow TP Reduced	2 (50%)		2 (33%)	1 (100%)	5 (71%)		2 (100%)	2 (100%)	
Events VBS Outflow TSS Reduced	2 (50%)		3 (50%)	0 (0%)	6 (86%)		1 (50%)	2 (100%)	
Total Flow Volume (m^3)	99		745	55	357		921	498	
Estimated TP Load Reduction (g)	-1.1		-28.9	6.9	0.2		4.2	8.1	

2.5. Discussion

2.5.1. Vegetated buffer strip performance for phosphorus retention

The findings of this study suggest that VBS are not consistently effective at reducing P concentrations and are not likely to reduce P loads substantially in cold climates such as those in the Canadian Prairies. This is especially true for soluble P (i.e. TDP), which was the dominant form of P in runoff during this study (over 70%). From the fall of 2015 to the spring of 2017, only nine of the 22 events monitored resulted in a reduction in mean TDP concentration after passing through the VBS. The VBS performed better at reducing TP concentrations than TDP, reducing mean concentrations in 14 of the 22 events. The inconsistent performance of VBS for reducing P concentrations supports the previous findings of Sheppard et al. (2006, 2012), and Habibiandehkordi et al. (2017) in VBS studies in the same region.

The VBS effect on TDP and TP concentrations was not statistically different than the effect of the annually cropped control strips. However, there was a substantial difference when comparing the VBS and control strips for their effect on TSS. The control strips increased mean TSS concentrations by 23% while the VBS reduced it by 30%. The increase in TSS in the control strips can be explained by the resuspension of soil particles in the runoff flowing over bare ground and disturbed soil caused by tillage operations. This corroborates previous research that suggests VBS are more efficient than cultivated land for trapping and removing suspended or particulate material, including sediment-bound P, but are inconsistent for retaining soluble forms of P (e.g. Magette et al., 1989; Gitau et. al., 2005; Uusi-Kämppä, 2005; Hoffmann et al., 2009).

Seasonality is an important factor that influences the performance of the VBS. There was very little change in P concentrations during spring events that were predominantly snowmelt driven or artificially induced runoff. This has been attributed to a variety of factors including the vegetation in the VBS being flattened by snow, reducing its roughness and trapping efficiency, the fact that soils are frozen and infiltration is limited, and low plant and microbial uptake of P during this period (Syverson, 2005; Shepaprd et al. 2006; Habibiandehkordi et al., 2017). Similar to other studies in cold climates, the VBS were more effective at retaining P during the growing season than other seasons (Schwer and Clausen, 1989; Schellinger and Clausen, 1992; Syverson, 2005). In this study, TP concentrations in the growing season were reduced by an average of 8.7%, although this was not statistically significant. On an event basis, the VBS also performed well during the growing season, reducing mean TP concentrations in five out of seven events (i.e. 71% of events). The VBS performed poorly in the fall, on average increasing the overall mean TP concentration (i.e. mean of all data for all events) and reducing TP concentration in just 33% of the events. The VBS increased TDP in five out of six events in the fall (i.e. 83% of events). It is noteworthy that all of the fall events were artificially induced.

The type of event, whether natural, artificial, or pond outflow, had a substantial effect on P transport and retention in this study. Artificial events were low in TP (mean VBS inflow of 110.7 µg/L) compared to pond outflow and natural events (216.1 µg/L and 650.2 µg/L, respectively). During artificial events, the VBS increased mean TP concentrations by 10%. All of these events occurred outside the growing season. Both the natural events and pond outflow events showed modest mean TP concentration reductions by the VBS of 5.5% and 9.8%, respectively. There were no natural or pond outflow events in the fall. The data from this study suggests that the fall time period may be a critical period for VBS to become a source of P to runoff, possibly attributed to P release from senescing and decaying vegetation (Uusi-Kämppä, 2005).

2.5.2. Study limitations

The relatively poor performance of the VBS in comparison to the control strips for P retention can be partially explained by the experimental design. Each VBS and control strip had either a weir or an outlet pipe at its outflow location. Although these type of structures are necessary for measuring water levels and flow and to create a point of runoff concentration required to collect water samples, they clearly alter the hydrology of these areas and could affect the mechanisms by which VBS function. VBS are reported to perform better with shallow diffuse flow conditions (Owens et al., 2007; Knight et al., 2010; Pankau et al., 2012). The weirs and pipes back-up water and create a ponding zone upstream, an area of deeper water with lower velocity. The deeper water, in some cases over 20 cm, could negatively affect the performance of the VBS if the water depth is greater than the vegetation height, which is common in the spring due to flattened vegetation and in the fall if the VBS is harvested. The ponding zones upstream of the weirs and pipes are likely to contribute to some settling of sediment and particulate P and increase the area and time for runoff waters to interact with the soils and the near surface vegetative residues. This could explain why the control strips displayed some evidence of P retention, sometimes outperforming the VBS for the retention of soluble P.

The VBS sites in this study were relatively young, with all events occurring within 2 years of the time they were seeded in the spring of 2015. The vegetation was slow to establish and plant density was low in the first year due to dry conditions. It is likely that the key VBS processes, including sediment trapping, plant nutrient uptake, and infiltration, will increase as the sites mature, the plant density increases and the soil and root structure continue to develop. For these reasons, continued monitoring of these sites is required to better understand and assess their potential.

In order to capture the effects of changing conditions throughout an event, it is necessary to get multiple water samples that are representative of each event. Important factors, including runoff depth, velocity and the related sediment and nutrient concentrations, will change during the course of an event. Repeated visual observations from this study suggest that runoff in the early portion of events is more turbid and contains more sediment than later in the event (Figure 2.28). Therefore, depending on the point at which a sample is taken, it could misrepresent the runoff at that site. Event mean concentrations or flow-weighted means derived from multiple samples taken during the rising and falling limbs of the event hydrograph would reduce the potential for misrepresentation and error.

Figure 2.28. Water samples taken 6 hours apart during an event in June 2016. The turbidity of the samples decreased during the event.

Accurate flow data were not available during this study, mainly due to issues with submerged weirs and flow meter limitations during low flow. Most studies of the efficacy of practices for nutrient retention are assessed using load calculations to determine the mass of the constituent retained or prevented from entering downstream waterbodies. The potential for reduced runoff volumes, an important process by which VBS can be effective, was not accounted for in this study. Flow measurements would allow valuable performance comparisons between sites expressed in similar terms (i.e. mass per unit area that the practice has removed or retained). This type of assessment would facilitate broader and more strategic targeting of practices and the setting of objectives aimed at load reduction at a watershed scale.

2.6. Conclusions

2.6.1. Research Questions

2.6.1.1. Do vegetated buffer strips lower phosphorus concentrations in surface runoff in cold climates?

Throughout the study period, there was no statistical difference between the inflow and outflow concentrations of TP or TDP in the VBS treatments.

2.6.1.2. How do annual crop strips compare to vegetated buffer strips for phosphorus concentration reduction in surface runoff?

There was no statistical difference between the control strips and the VBS plots for reducing P concentrations. However, when considering mean reductions in concentrations overall, the VBS plots performed slightly better for TP while the control strips outperformed the VBS for TDP by a small margin. The VBS was substantially better at removing TSS from surface flow.

This study supports previous research that VBS perform best during the growing season. However, this study was limited in the amount of natural runoff events that occurred outside the growing season, especially in the fall. This may be a critical period for future study as this is when the vegetation and plant residue amounts are considerably higher in the VBS than the annual crop strips and P is highly susceptible to release from the senescing and decaying plant material (Sharpley, 1981; Rekolainen et al., 1997; Cronk and Fennessy, 2001; Bechmann et al., 2005; Kröger et al., 2007; Roberson et al., 2007; Øgaard, 2015; Lozier et al 2017). Although, this study benefited from the artificially induced runoff that created additional events and more samples to be collected and for different time periods, it is clear that these events were not typical of runoff for this agricultural region. The mean TP in natural runoff was substantially higher, by nearly five times, than the artificial events. The low TP artificial runoff may be more likely to desorb and transport nutrients, especially in dissolved form. The potential for increased transport of dissolved P is exacerbated if the runoff occurs over areas with saturated soil P or if there are significant sources of dead and decaying plant material on the soil surface. These conditions have been shown to be when VBS are especially susceptible to P release.

The results of this research, although not statistically conclusive, support some recommendations for future research directions for VBS in cold climates. Further study of the non-growing season performance of VBS would help to determine why they may not be as effective during these time periods. Modifications to the experimental and site designs should be pursued to assess optimal VBS performance in this climate. Conditions and site modifications that minimize deep concentrated runoff and promote shallow diffuse flow should be explored and studied. For example, the VBS sites can be contoured so that the runoff is spread out over a wider and flatter area (i.e. level spreader designs).

This study site benefited from two retention ponds that stored and treated runoff from the agricultural fields and allowed for controlled releases through two of the VBS sites. The combination of VBS and retention pond practices is worthy of future study. Not only does the VBS provide a secondary treatment mechanism, but a retention pond would allow some control over when runoff or water flow occurs through a VBS site. If possible, water in the ponds could be retained and released at optimal times for VBS nutrient removal (i.e. dry antecedent conditions during the growing season).

This study supports previous findings that VBS are inconsistent at retaining P in cold climates. It provides insight into when and why VBS sites may perform better. It strengthens the basis to direct future research and VBS designs in cold climates, including methods to reduce vegetative P sources outside the growing season (e.g. harvest vegetation) and promote conditions that improve VBS function during all seasons (e.g. alter flow from contributing areas from deep and concentrated to shallow and diffuse).

3. Spatial and temporal patterns of phosphorus in soils and above-ground vegetation in vegetated buffer strips in cold climates

3.1. Introduction

Vegetated buffer strips (VBS) are implemented around the world as a mechanism to retain phosphorus (P) in agricultural landscapes. However, poor or inconsistent performance of VBS for P retention has been reported in multiple studies from cold regions in North America and Europe (Schellinger and Clausen, 1992; Uusi-Kamppa, 2005; Habibiandehkordi et al., 2017). One of the potential reasons for this discrepancy with studies from warmer climates, that suggest VBS are very effective for retaining runoff P, stems from the mechanisms that allow VBS to retain P. One of these mechanisms is the retention of P in VBS soils. Infiltration and adsorption of runoff P in the soil is reported as one of the main retention mechanisms in a VBS, especially for the dissolved P fraction (Lee et al., 1989; Barfield et al., 1998). Deposition of sediment also contributes to P enrichment of VBS soils (Cooper et al., 1995; Sheppard et al., 2006). Over time, this accumulation can lead to soil P saturation in the VBS, causing them to become a source of P to overland flow (Kleinman et al., 2011). The retention capacity of P in a VBS has been shown to decrease with increasing soil P saturation (Pant et al., 2002; Pant and Ready, 2003; Liikanen et al., 2004).

Plant uptake of P is another important process by which VBS have been reported to capture and retain P (Lee et. al., 1989; Dabney et al., 2006). However, plant retention of P in the above-ground biomass is considered temporary because much of the P is lost after senescence and decomposition (Cronk and Fennessy, 2001). The process of nutrient loss from decaying plant material is even more pronounced in cold climates where freezing and thawing cycles cause more dissolved P to be released from vegetative residues (Miller et al., 1994; Bechmann et al., 2005; Roberson et al., 2007; Elliott, 2013; Liu et al., 2013b; Riddle and Bergström, 2013; Kieta, 2017).

Although previous studies have suggested that VBS sites may accumulate P, there has been little research to assess the spatial and temporal patterns of P in soils within a newly established VBS in a cold climate. Similarly, few studies have investigated how much P is stored in a VBS in above-ground plant material. The quantification of P levels is soil and plant material over time and a comparison among seasons will provide insight into conditions and time periods when a VBS may become a source of P to overland flow. A comparison of VBS soil and vegetation P retention patterns to that of the “business as usual” or control case, namely annually cropped strips, in cold climates is also currently lacking in the literature.

The objectives of this study were:

- to assess temporal and spatial trends in soil P in a VBS (by slope and longitudinal position);
- to assess whether the temporal and spatial soil P patterns in a VBS differ from annual crop strips;
- to quantify the amount of P that can be removed from VBS sites by harvesting vegetation; and
- to investigate changes in P content of vegetative residues within a VBS from the fall to spring and to compare values to annual crop strip residues.

The research questions to be investigated during this study were:

1. Do newly established VBS accumulate P in the soil over time? If so, where?
2. Do annual crop strips in a concentrated overland flow path accumulate P in the soil? If so, where?

3. Does vegetation harvesting remove substantial amounts of P from a VBS?
4. Do vegetative residues represent a substantial source of P to surface runoff in a VBS?

3.2. Methods

3.2.1. Site description

See Section 2.2.1

3.2.2. Vegetated buffer and control strip plot establishment

See Section 2.2.2

3.2.3. Zonation of vegetated buffer and control strip plots for soil and vegetation sampling

To facilitate the comparison of different vegetative, soil, and hydrological conditions, the VBS and control strip plots were divided into different zones based mainly on their slope position and vegetation composition. All sites were divided into lower slope (LS) and mid-slope (MS) zones. The moisture conditions within the plots heavily influenced the vegetation composition and therefore were factored into the delineation of the zones. The LS zone in the VBS plots was an area that was frequently inundated during runoff events and consisted of species that were better adapted to wet conditions, while the MS zone consisted of species that were more suited to drier, slightly saline conditions. The LS zone in the VBS plots contained more tall grass species including meadow foxtail (*Alopecurus pratensis*), cattail (*Typha spp*.), and reed canary grass (*Phalaris arundinacea*), while the MS zone was dominated by short grass species including foxtail barley (*Hordeum jubatum*), alkali grass (*Puccinellia spp.*), and sheep fescue (*Festuca ovina*).

Previous studies have reported that most of the sediment deposition occurs in the first few meters of a VBS, especially for the coarser particles (Hussein et al. 2007; Owens et al. 2007). For this reason, the LS zone was further divided by its longitudinal position or distance parallel to the flow-path into the VBS. The lower-slope upstream (LS-U) zone extended the first five meters into the VBS (i.e. 0 – 5 m) while the lower-slope downstream (LS-D) zone consisted of the remaining 15 m (i.e. 5 – 20 m). Because the control strip zones were cultivated and seeded to a monoculture annual crop every year, zone delineation could not be based on vegetation species. Instead, the zones within the control strip plots were mainly delineated based on their slope and generally coincided with the adjacent VBS zones (i.e. slope position in the VBS extended into the control strip). Additionally, soil conditions (i.e. evidence of water logging) and crop health (i.e. observations of moisture induced stress) were taken into account when delineating the control strip zones. All VBS and control strip zones were mapped using a survey grade global positioning system (Figure 3.1).

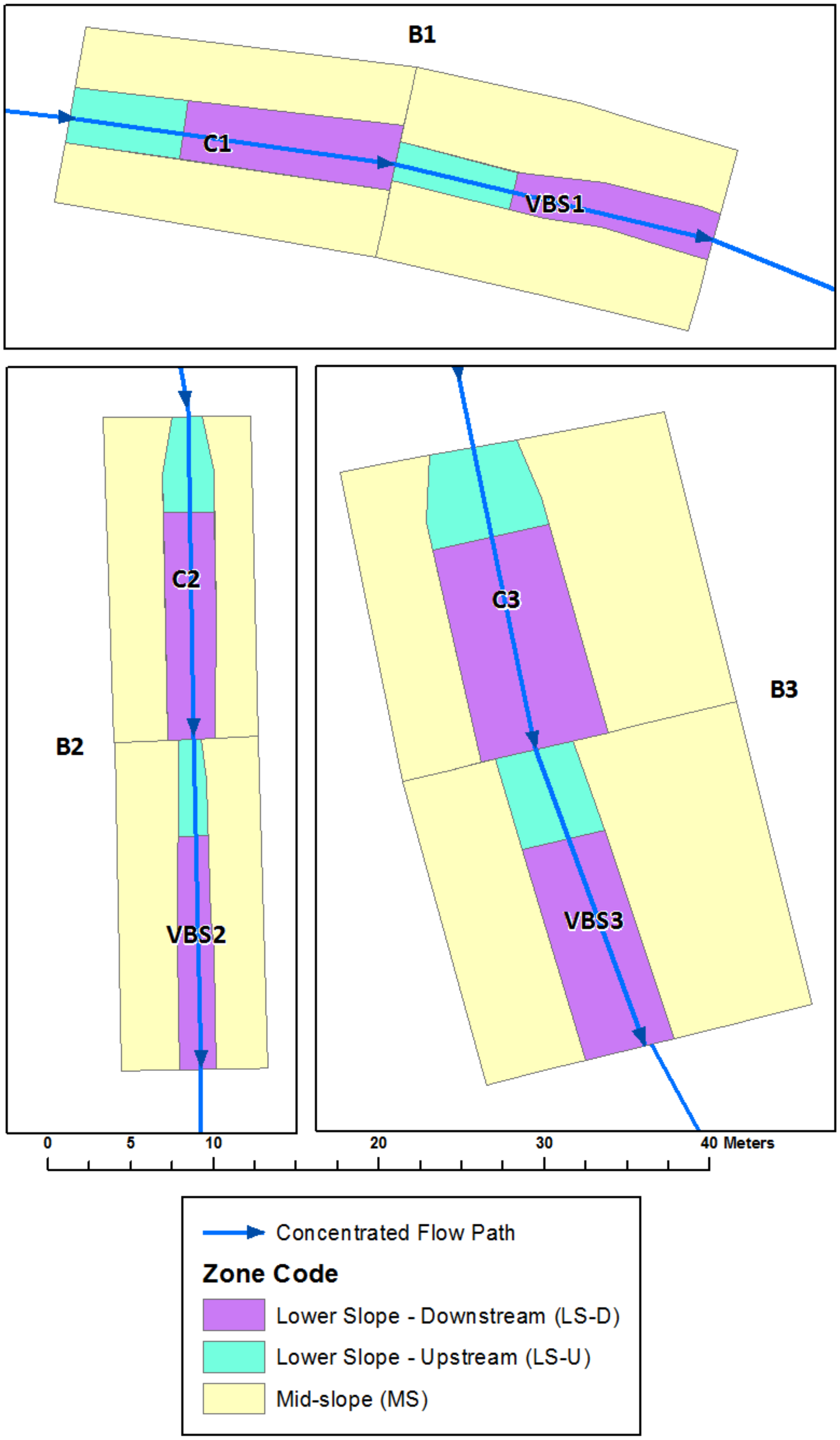

Figure 3.1. Zonation of vegetative buffer strip (VBS) and control strip (C) plots by slope and longitudinal position.

3.2.4. Soil sample collection and analysis

Soil samples in all of the VBS and control strip zones were collected in the spring (May) and fall (October) of 2016 and in the spring (May) of 2017. The sampling procedure included collecting composite samples using a JMC Backsaver Hand Soil Sampler. The composite samples consisted of a minimum of three subsamples from each zone at depths of 0-5 cm, 5-15 cm, and 15-60 cm. However, only the 0-5 and 5-15 cm depths were consistently collected throughout the entire study period, and were often combined (i.e., 0-15 cm).

All soil samples were sent to Farmer's Edge Laboratory (Winnipeg, MB) and analysed for Olsen P, Total P, Nitrate-Nitrogen, organic matter, pH, and electrical conductivity. Although nitrogen (N) was not the focus of this study, this analysis was included as it was part of a broader study and was also informative for interpreting some of the P data described below (e.g. Section 3.3). Prior to analysis, samples were dried at 40°C and ground. The following are procedures for the analyses provided by Farmer's Edge Laboratory:

"Bicarbonate Extractable Phosphorus (Olsen P)

Bicarbonate extractable P, or Olsen P, was determined by adding 50 mL of 0.5M $NaHCO^3$ *to 2.5 g of soil. This solution was shaken for 30 minutes, filtered, and after a reduction by ascorbic acid and complexation with ammonium molybdate, measured by automated colorimetry. Bicarbonate extractable phosphate-P is reported as mg/kg after being measured by automated segmented flow colorimetry using a SAN ++ system (Skalar, Breda, The Netherlands).*

Nitrate-Nitrogen

Nitrogen (N) reported as nitrate (mg/kg) was analyzed by adding 30 mL of 0.01M $CaCl^2$ *to 15 g of soil. This mixture was shaken on a reciprocating shaker for 30 minutes and then filtered. After a hydrazine reduction and complexation with n-(1naphthyl) ethylenediamine dihydrochloride,* NO^3*-N was measured by automated segmented flow colorimetry using a SAN ++ system (Skalar, Breda, The Netherlands) and reported as mg/kg.*

Total Phosphorus

Total P, reported in mg/kg, was analysed by digesting 1 g of dried, ground soil with microwave assistance in 10 mL of concentrated nitric acid, to solubilize all elements. The digested material was diluted with ultrapure water and was analyzed using an inductively-coupled plasma optical spectrometer (ICP-OES) (Thermo Electron ICAP 6300, Cambridge, UK).

Percent Organic Matter

Loss on ignition, a dry combustion method, was used to determine percent organic matter (%OM). 2.5 g of sample were dried at 104°C for two hours to remove all atmospheric moisture. The sample was then ashed at 375°C for two hours to oxidize the organic carbon and remove it in the form of CO^2*. The sample was again weighed and the results are reported as %OM."*

3.2.5. Vegetation and residue sample collection and analysis

Samples of harvestable vegetation, or plant material above approximately 15 cm in height, representing the portion that could be cut and removed by commercial scale farm equipment, were collected prior to harvest in the late summer (September) of 2016. For VBS plots, harvesting consisted of cutting the vegetation with a sickle mower and removing the cut material by hand (to simulate cutting and baling of a perennial forage crop). Harvesting the control strip plots was conducted using typical large scale farming methods, including cutting with a swather and threshing by a combine. Vegetative residue samples, consisting of all plant material remaining above the soil surface after harvest, were collected in the fall (November 2016) and again in the following spring (April 2017). For both the harvestable vegetation and the plant residue samples, three duplicate samples from a 50 cm by 50 cm area were collected in each of the four zones (LS-U, LS-D, and the two MS zones) within each plot. To better capture variability of the vegetation within each zone, each sample was analyzed individually (i.e. samples from the same zone were not combined to make a composite sample as was done for the soil). After collection, all harvestable vegetation and plant residue samples were dried at 40°C for a minimum of 72 hours until their mass remained relatively constant (i.e. within 2% of its previous measurement). After recording the dry mass, the samples were sent to Farmer's Edge Laboratory (Winnipeg, MB) and analysed for Total P using the same procedure as for soil samples and reported as percent P (see Section 3.2.4).

3.3. Results

3.3.1. Soil phosphorus, nitrogen, and organic matter analysis and patterns

Bicarbonate extractable soil P (Olsen P) levels are strongly correlated with the leaching potential of soils and water extractable P, which is the most bioavailable fraction (Andersen et al., 2016). Thus, Olsen P is a robust method to predict P losses in runoff from agricultural soils in Manitoba (Kumaragamage et al., 2010). For this reason, Olsen P was used in this study for investigation of spatial and temporal patterns within the VBS and control strip plots. Because the only consistent depth used throughout the study was 0-15 cm, all analysis relate to this sampling depth. The mean Olsen P in the VBS soil was slightly lower than the control strips (17.0 mg/kg and 19.5 mg/kg, respectively). However, due to substantial variability (Figure 3.2), the medians were not statistically different at $p<0.05$ according to the Mann-Whitney Rank Sum Test for non-normal data (P=0.171). The mean nitrate-nitrogen levels in the VBS soil was lower than the control strips (2.9 mg/kg and 17.7 mg/kg, respectively). The higher nitrate-nitrogen and Olsen P levels in the control strip plot soils are likely attributed to the annual fertilizer amendments.

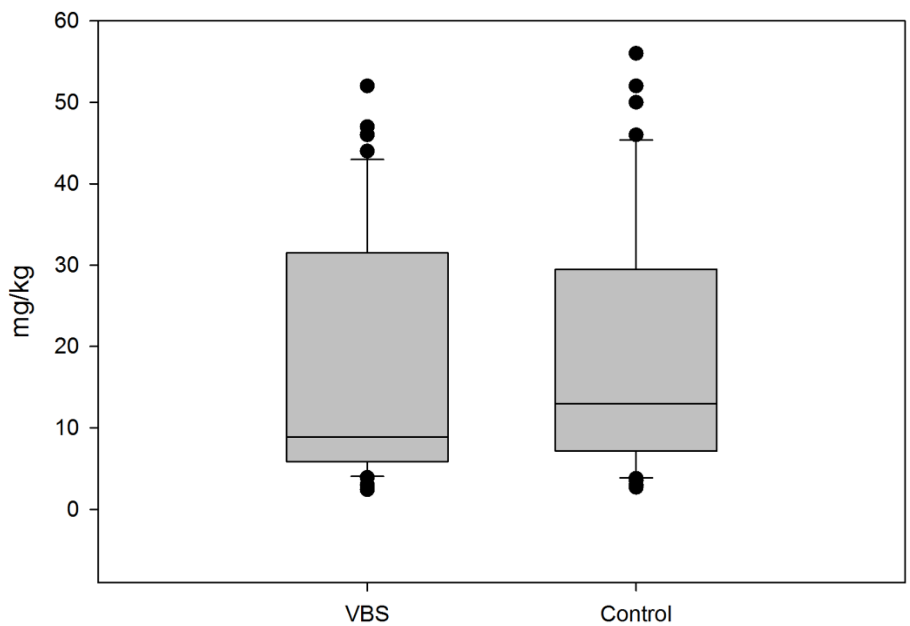

Figure 3.2. Soil Olsen P (0-15 cm depth) for vegetated buffer strip (VBS1-VBS3) and control strip (C1-C3) plots

There was substantial variability in soil P between the different sites as shown in Figure 3.3. The plots at site B1 (i.e. VBS1 and C1) had higher mean Olsen P at 0-15 cm depth (> 36.5 mg/kg) compared to the other plots at sites B2 and B3 (< 11.1 mg/kg). Lower levels in the plots at sites B2 and B3 (i.e. plots VBS2, VBS3, C2, and C3) can be attributed to the excavation and removal of some of the top soil in 2014 prior to establishing the plots for this study.

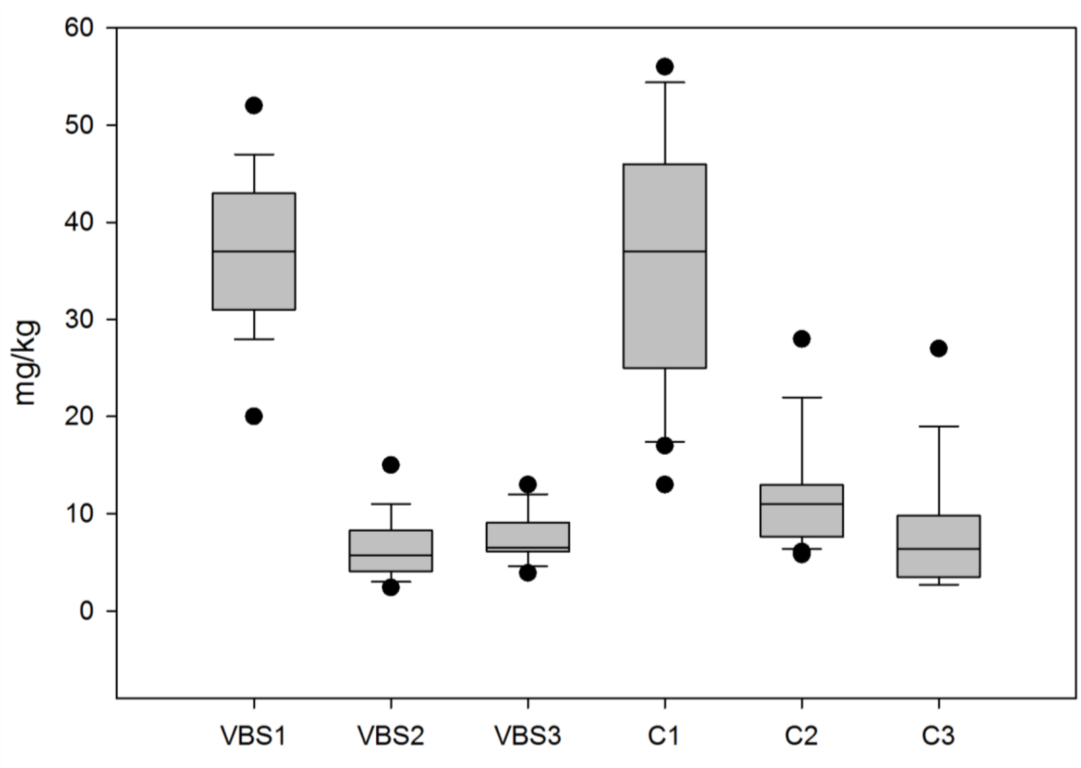

Figure 3.3. Soil Olsen P (0-15 cm) for vegetated buffer strip (VBS) and control strip (C) plots

For all samples analyzed during this study, soil total P (TP) at the 0-15 cm depth varied considerably between the different VBS and control strip plots (Figure 3.4). Similar to Olsen P, the plots at Site B1 had the highest levels of soil TP at this depth (a mean of 666.3 mg/kg of TP for VBS1 and a mean of 647.0 mg/kg of TP for C1). The lowest levels of soil TP were found at site B2 (VBS2 and C2) followed by site B3 (VBS3 and C3), with these four plots ranging from a mean of 517.3 mg/kg in plot C2 to a mean of 584.3 mg/kg in plot C3. Overall, the VBS plots had a slightly larger mean TP content than the control strip plots (a mean of 589.1 mg/kg and 582.8 mg/kg respectively). The difference between VBS and control strip treatments for soil TP was not statistically significant (Two-tailed T-Test, P=0.626).

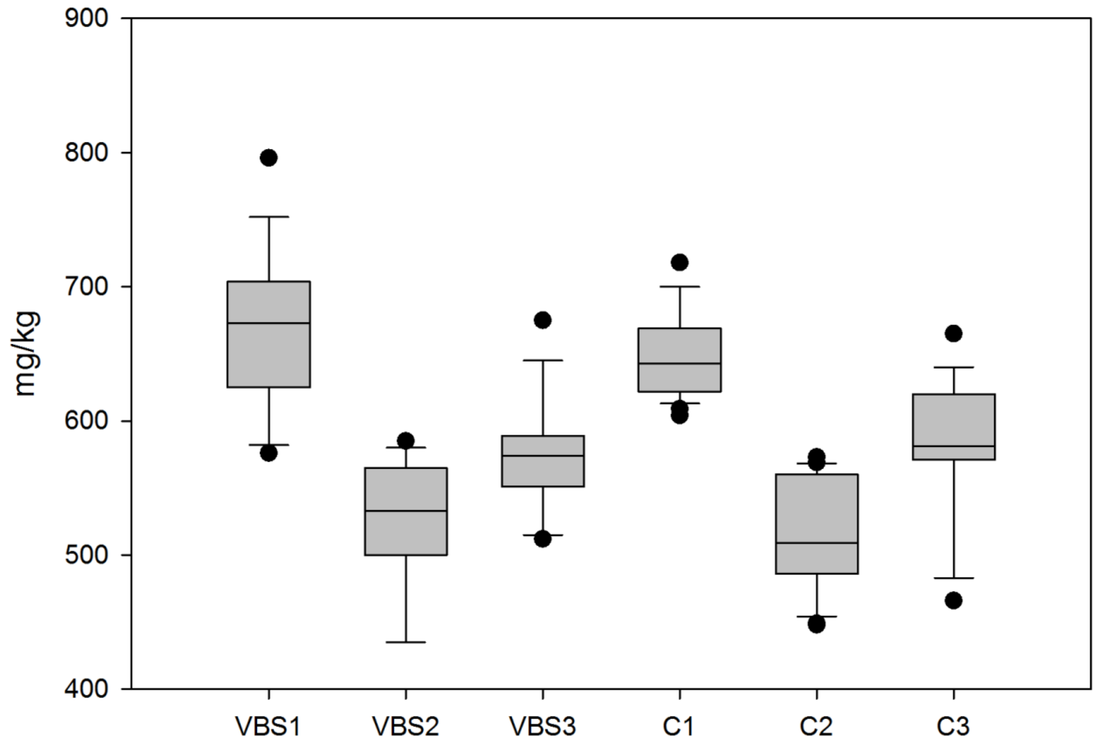

Figure 3.4. Soil total P (0-15 cm) in vegetated buffer strip (VBS) and control strip (C) plots

Soil organic matter at 0-15 cm depth exhibited less variability between the different VBS and control strip plots (Figure 3.5) than the nutrient levels, with a relatively narrow range of mean levels from a low of 3.32% in plot C3 to 3.64% in plot VBS3. Overall, the VBS plots had a slightly larger mean organic matter content than the control strip plots (a mean of 3.54% and 3.47% respectively). The difference between VBS and control strip treatments for organic matter was not statistically significant (Mann-Whitney Rank Sum Test, P=0.764).

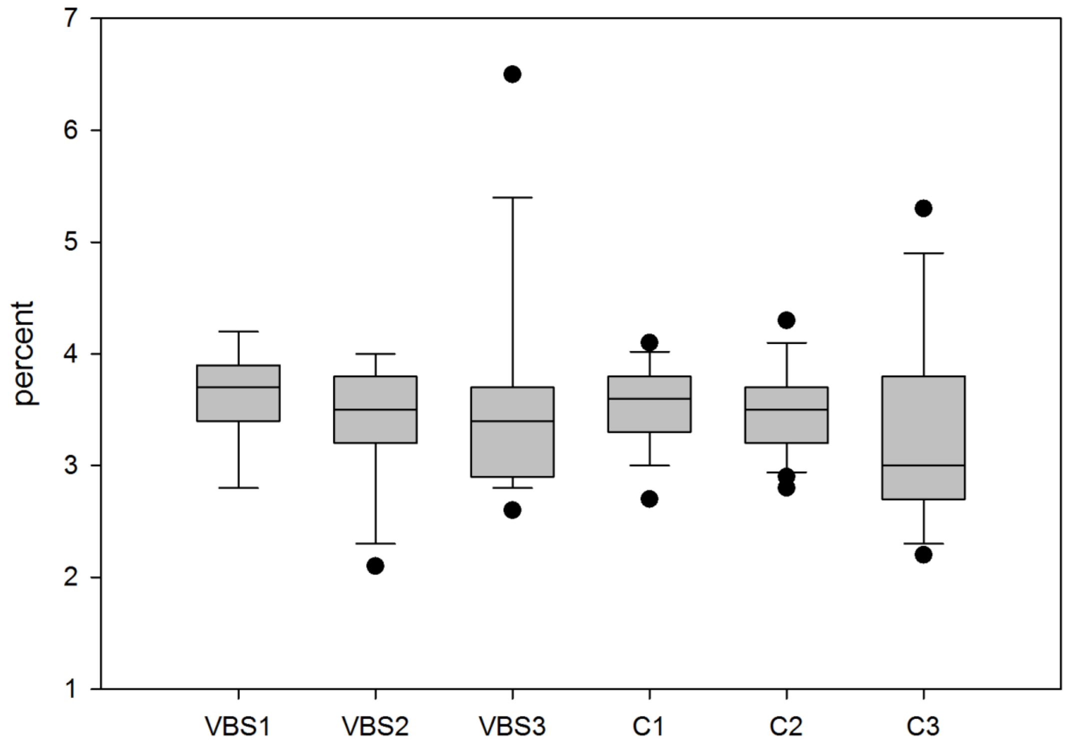

Figure 3.5. Soil organic matter (0-15 cm) in vegetated buffer strip (VBS) and control strip (C) plots

3.3.1.1. Temporal patterns in soil phosphorus and nitrogen

Soil nutrient levels varied substantially by season (Figure 3.6). Olsen P was higher in the spring than the fall (median values of 21.4 mg/kg and 16.3 mg/kg, respectively) although this difference was not statistically different at $p<0.05$ (Mann-Whitney Rank Sum Test for non-normal data, $P = 0.081$). Although N was not the focus during this study, the data for soil nitrate was also presented in Figure 3.6 to further illustrate the seasonal dynamics of nutrient levels in the soil. The seasonal difference was more pronounced with soil nitrate, with median spring levels significantly higher than fall (9.7 mg/kg and 2.6 mg/kg, respectively, $P<0.001$).

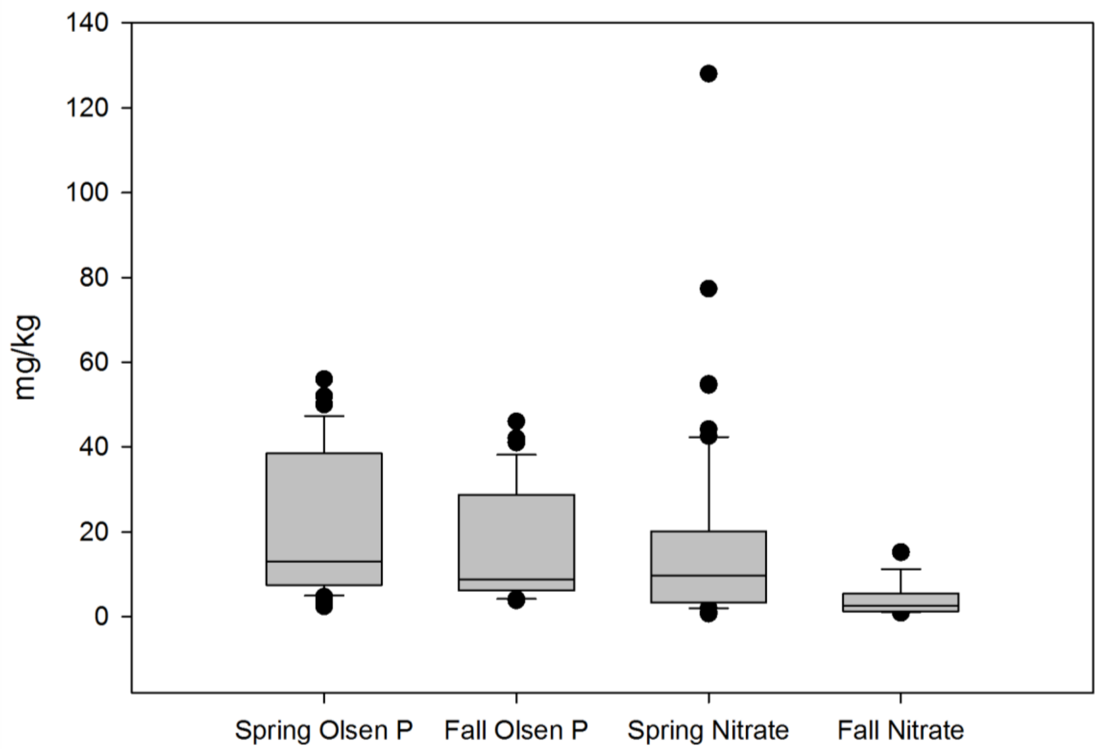

Figure 3.6. Soil Olsen P and nitrate (0-15 cm) in the spring and fall of 2016 for all plots including both vegetated buffer and control strip plots (i.e. VBS1-VBS3 and C1-C3 combined)

When comparing data from spring of 2016 to spring of 2017, mean Olsen P in the VBS plots increased substantially from 16.9 mg/kg to 20.5 mg/kg, an increase of 21.3% in a single year without the addition of fertilizer (Figure 3.7). Mean Olsen P in the control strip plots remained relatively constant, 23.1 mg/kg in spring of 2016 and 23.5 mg/kg in spring of 2017, a difference of only 1.7%. Although mean Olsen P was considerably higher in the VBS plots in 2017, there was considerable variability in the data and the difference in the medians was not statistically significant at $p<0.05$ (Mann-Whitney Rank Sum Test for non-normal data, $P=0.189$ for VBS plots; $P=0.704$ for control strip plots).

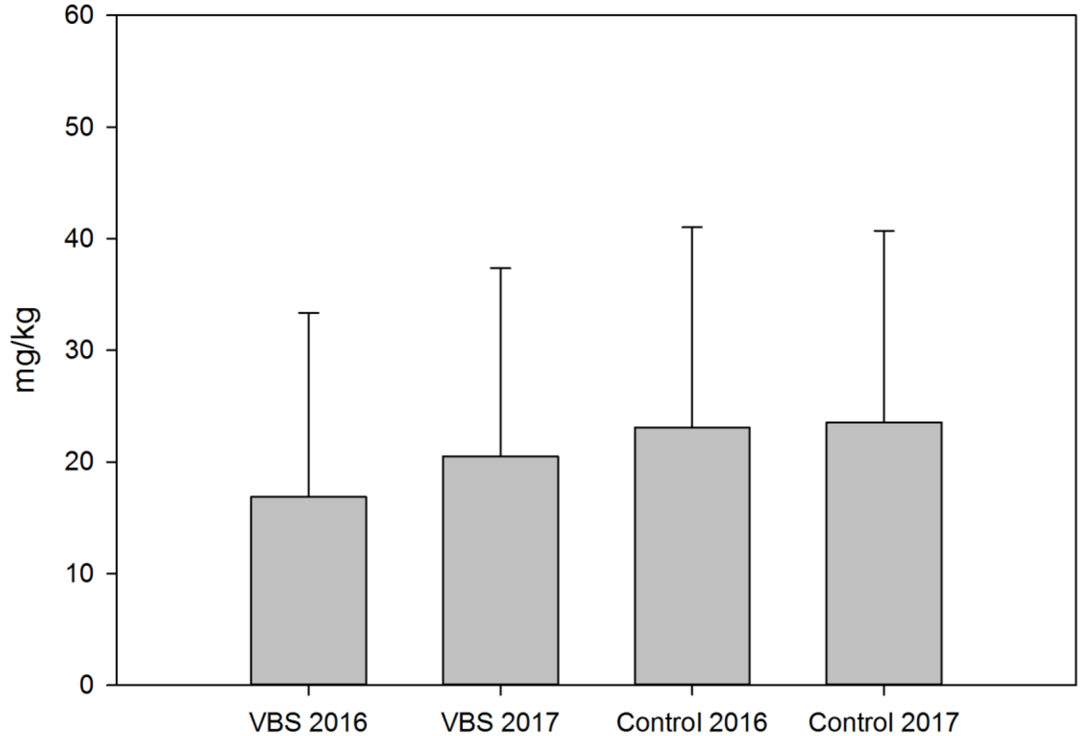

Figure 3.7. Soil Olsen P (0-15 cm) in spring in 2016 and 2017 in vegetated buffer strip (VBS1-VBS3) and control strip plots (C1-C3)

3.3.1.2. Spatial patterns in soil phosphorus

When the data from the VBS and control strip plots were combined, slope positon had little effect on Olsen P. This was evident when comparing the LS zone to the MS zone, Olsen P was highly variable with median values slightly higher in the LS zone while the mean values were slightly lower (Figure 3.8). However, due to variability in the data there was no statistical difference in the medians at $p<0.05$ (Mann-Whitney Rank Sum Test for non-normal data, $P=0.650$).

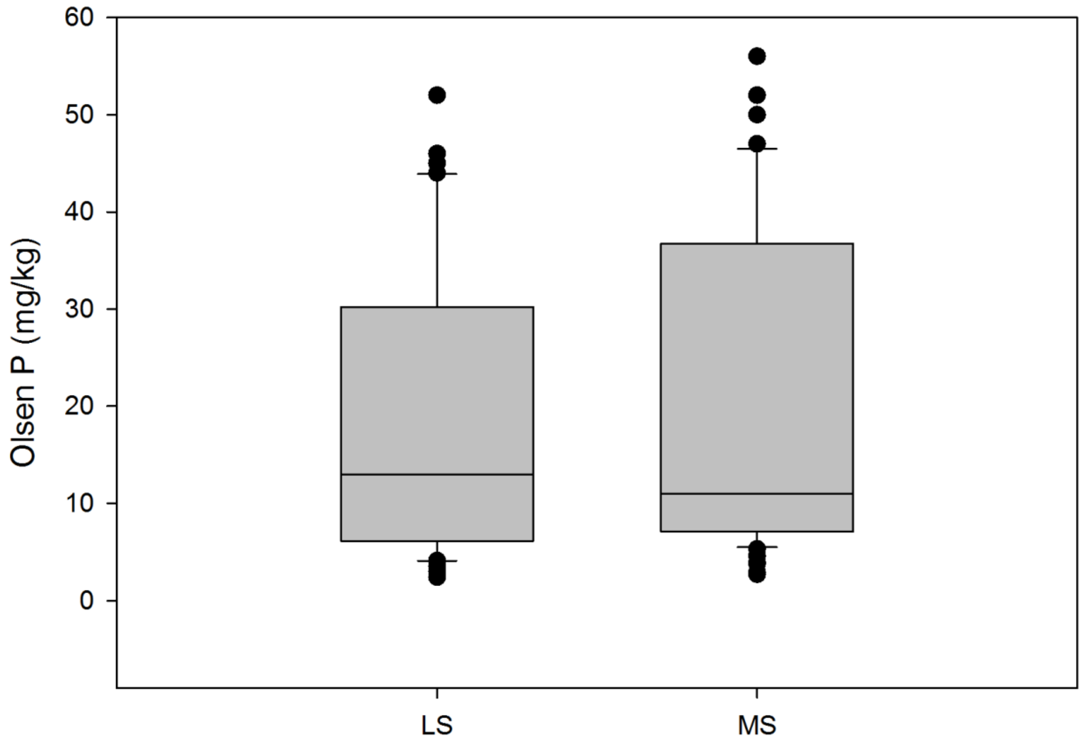

Figure 3.8. Soil Olsen P (0-15 cm) by lower slope (LS) and mid slope (MS) position zones for all data including both vegetated buffer strip and control strip plots (i.e. VBS1-VBS3 and C1-C3 combined)

A comparison of Olsen P in VBS to control strip plots by slope position revealed some contrast between the treatments. In VBS plots, mean Olsen P was higher in the MS zones than the LS zones (18.3 mg/kg and 14.8 mg/kg respectively). Conversely, in control strip plots the LS zones had slightly higher mean Olsen P than the MS zones (20.3 mg/kg and 19.0 mg/kg respectively) (Figure 3.9). However, due to variability in the data, none of these differences were statistically significant at $p<0.05$ (Mann-Whitney Rank Sum Test for non-normal data, $P=0.060$ for VBS plots; and $P=0.342$ for control strip plots). Crop utilization of P was likely lower at LS zones due to excess moisture stress leading to P accumulation in these zones.

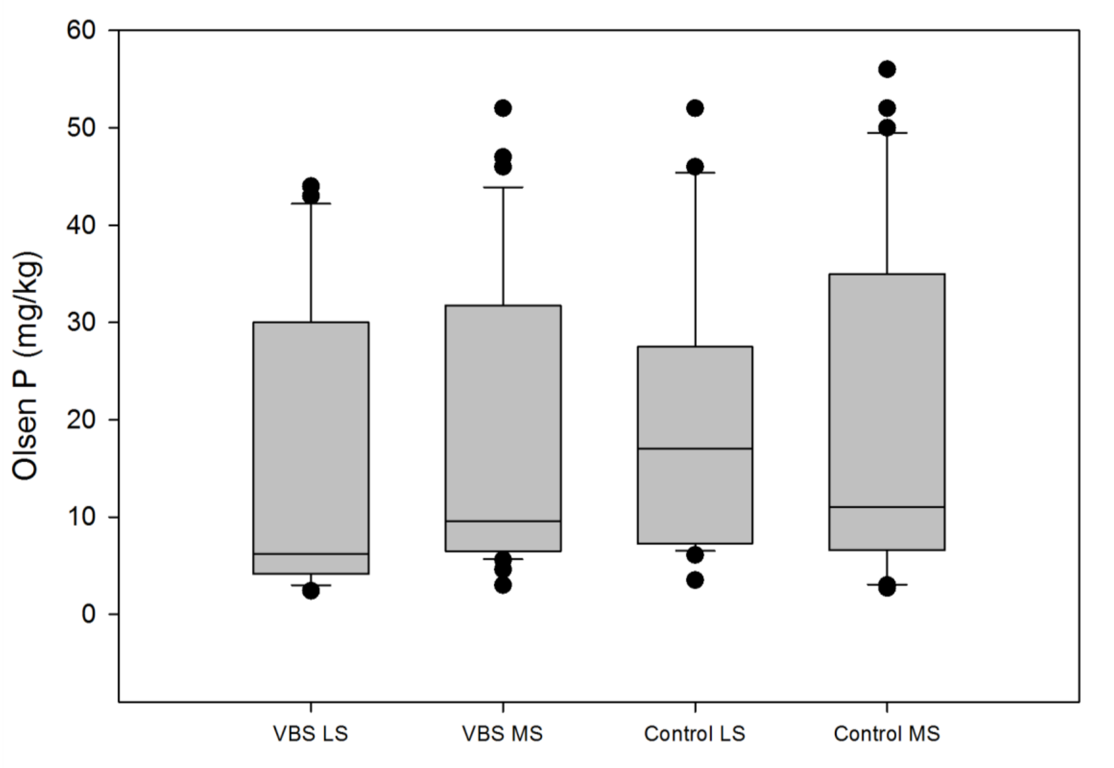

Figure 3.9. Soil Olsen P (0-15 cm) in vegetated buffer strip (VBS1-VBS3) and control strip plots (C1-C3) by lower slope (LS) and mid slope (MS) zones

3.3.1.3. Spatio-temporal patterns of soil P

From spring of 2016 to spring of 2017, mean Olsen P in the LS zone of the VBS plots increased from 15.4 mg/kg to 18.4 mg/kg, an increase of 19.5%. By comparison, mean Olsen P in the LS zones of the control strip plots increased, but less substantially from 22.4 mg/kg to 24.3 mg/kg or an increase of 8.5% (Figure 3.10). However, due to variability in the data, none of these differences were statistically significant at $p<0.05$ (Mann-Whitney Rank Sum Test for non-normal data, P=0.485 for VBS plots; and P=0.625 for control strip plots).

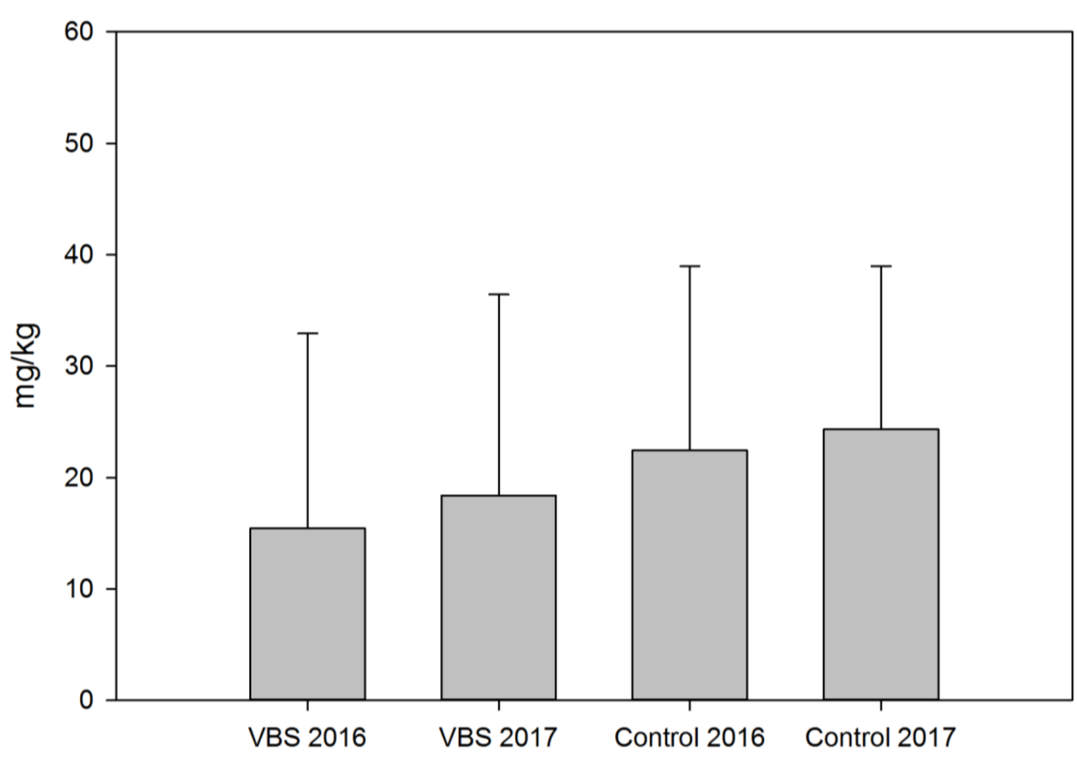

Figure 3.10. Soil Olsen P (0-15 cm) in spring 2016 and 2017 in lower slope zones of vegetated buffer strip (VBS1-VBS3) and control strip plots (C1-C3)

When comparing spring of 2016 to spring of 2017 in the LS-D zones (i.e. the downslope portion of the LS zone), the mean soil Olsen P increased substantially in just one year in both the VBS and control strip plots, an increase of 29.2% and 19.8% respectively (Figure 3.11). For the LS-U zones in the same time period, the mean Olsen P in the VBS plots increased (11.1%), while the control strip plots decreased slightly (-2.2%). Although there is considerable variability in these data and there are only two sampling times in just a 12 month period, this could be early evidence of P accumulation in LS-D zones in both VBS and control strip plots. These zones experienced periods of ponding during runoff events because they were upstream of weirs and outflow pipes, possibly leading to increased rates of sediment deposition and adsorption of P in the soil. Although preliminary, these data also suggests that the VBS LS-U zone is likely acting to filter sediment in the upstream or leading edge of the strip. This is less likely to occur in the control zones. Outside of the growing season, control zones have little vegetative cover and considerable amounts of bare soil, especially after tillage operations. In VBS sites, vegetative cover is generally present year round. Because it is difficult to support this theory with a small time series of data, further study is required to validate these trends.

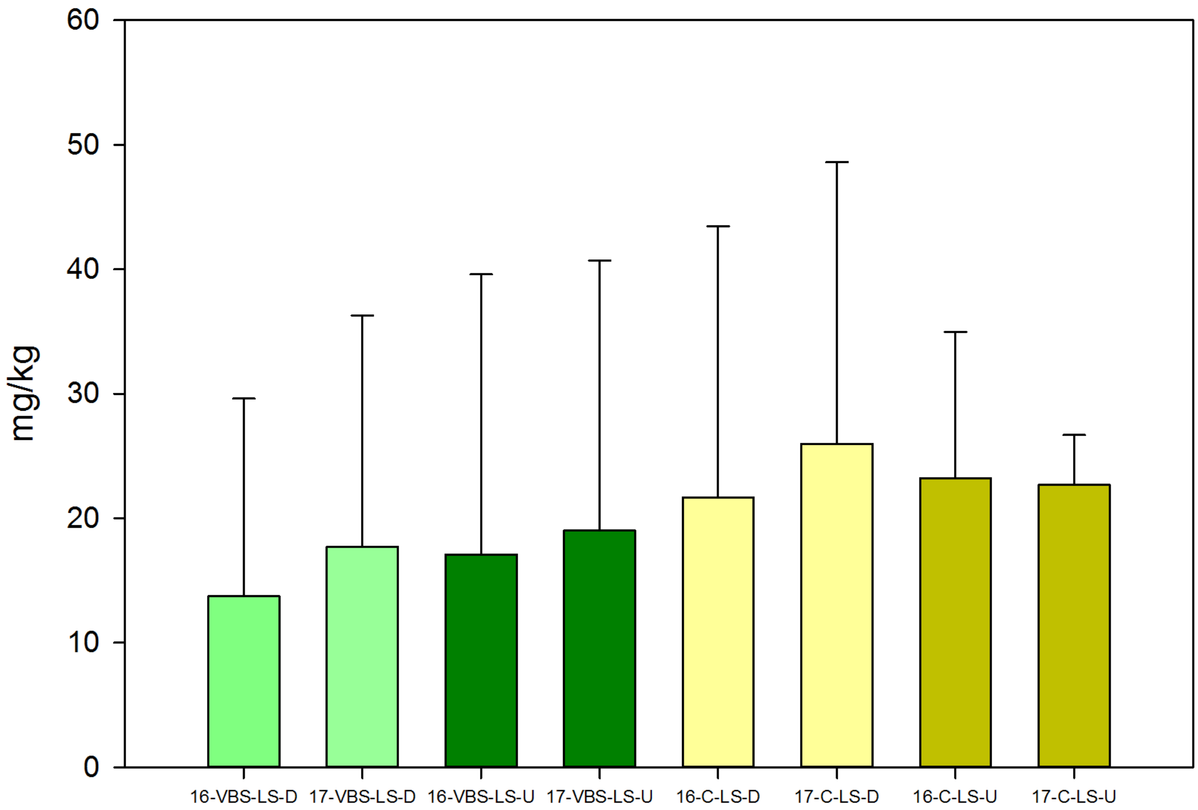

Figure 3.11. Soil Olsen P (0-15 cm) in spring 2016 (16) and 2017 (17) in vegetated buffer strip (VBS) and control (C) plots in lower-slope downstream (LS-D) and lower-slope upstream (LS-U) zones

3.3.2. Vegetation P analysis and patterns

3.3.2.1. Harvestable vegetation mass and phosphorus content patterns

The mean dry mass of harvestable vegetation, or plant material above 15 cm, in 2016 was greater in control strip plots than VBS plots, 2,050 kg/ha and 1,721 kg/ha respectively (Table 3.1). Although this is an accurate estimate of potential removal rates if this vegetation were cut and removed, which is feasible for VBS plots, this greatly overestimates removal rates in the control strip plots because only the grain portion of the crop is typically removed at harvest. Laboratory analysis of these samples showed that the mean percent TP content in the harvestable vegetation in the control strip plots was higher than the VBS, 0.27% and 0.20%, respectively. The higher mass and percent TP content in the controls led to a considerably higher mean mass of TP in the control strip plots compared to the VBS, 5.07 kg TP/ha and 3.33 kg TP/ha, respectively.

Table 3.1. Summary statistics for harvestable vegetation mass and TP content for VBS and control strip plots in the summer of 2016

	n	Mean	Median	Std. Dev.
VBS mass (kg/ha)	30	1,721	1,706	1,116
VBS TP %	30	0.20	0.19	0.07
VBS TP mass (kg/ha)	30	3.33	3.39	2.09
Control mass (kg/ha)	24	2,050	1,822	1,581
Control TP %	24	0.27	0.27	0.11
Control TP mass (kg/ha)	24	5.07	3.50	4.03

Due to different levels of soil fertility and different crops planted in the three control strip plots, there was considerable variability in the productivity and amount of harvestable vegetation in the different plots (Figure 3.12). Control plot C3, seeded to soybean, had similar harvestable vegetation mass to the other plots but the lowest percent TP content and the lowest TP mass.

Due to topsoil removal and the resulting lower soil fertility, the C2 plot had the lowest harvestable mass. Mean percent TP in the control strip plot C1 seeded to canola was 0.33%, the highest of all plots, including VBS plots. Plot C2, also canola was 0.29% TP, second only to C1, and plot C3 that was a soybean crop was only 0.14%, the lowest of all plots including VBS.

Mean TP content in the harvestable vegetation in VBS1 was 0.27% compared to 0.19% in VBS2 and 0.16% in VBS 3 (Figure 3.12). VBS1 also had the highest soil P levels. Although this is from just one instance in time and more data are needed, this may point to a relationship between high soil P and increased or “luxury” uptake of P in both annual crops and VBS plant species.

An analysis of harvestable vegetation by slope position showed that the LS zone for both the VBS and control strip plots tended to have lower mass than the MS zones (Figure 3.13). This is likely attributed to the ponding conditions and moisture stress on the vegetation in these zones, which was especially pronounced in the control strip plots. The percent TP content in the harvestable vegetation was higher in the LS zone for both the VBS and control strip plots. This may be due to a variety of factors including differing vegetation species throughout the zones as well as the fact that samples were not able to be included for the LS zone in C3 that was seeded to soybeans. The crop in this zone could not withstand the high moisture conditions that were more extreme in this plot due to its downslope location in close proximity to a nearby stream (Figure 3.14). This resulted in very little vegetation present at the time of sampling. Due to the substantially higher mass in the MS zones, these areas had higher mass of TP compared to the LS zones.

This shows that vegetation type is important in P uptake (i.e. soybeans have relatively low TP content compared to canola) and there is substantial variability in TP content in the control strip plots (mean of 0.27%, std. deviation of 0.11). More research is required to explain why the TP content is so variable and to quantify changes over time among the common VBS plant species in this region of southern Manitoba.

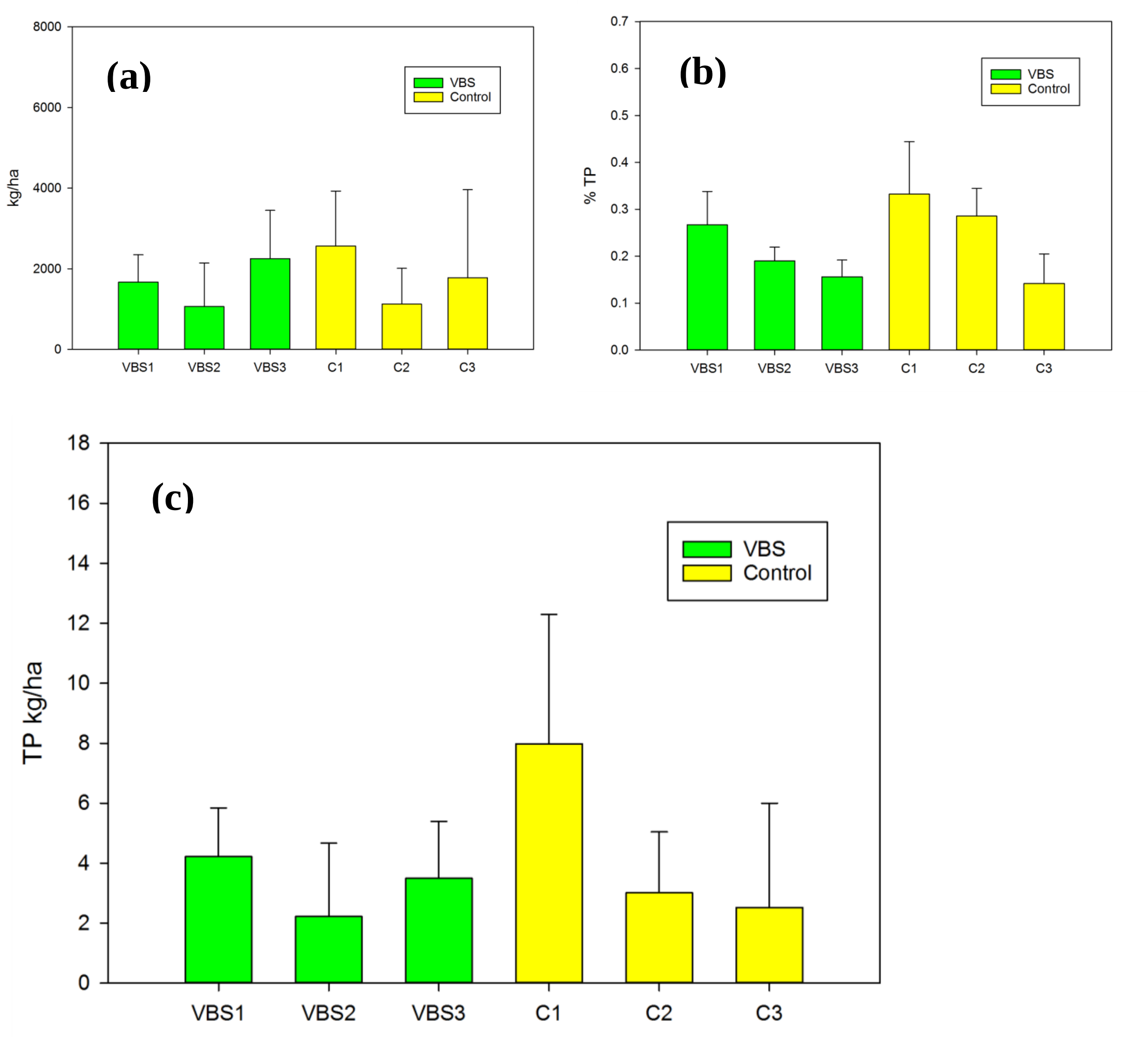

Figure 3.12. Harvestable vegetation mass (a), percent TP content (b), and TP mass (c), in each vegetated buffer strip (VBS) and control (C) plots in the summer of 2016

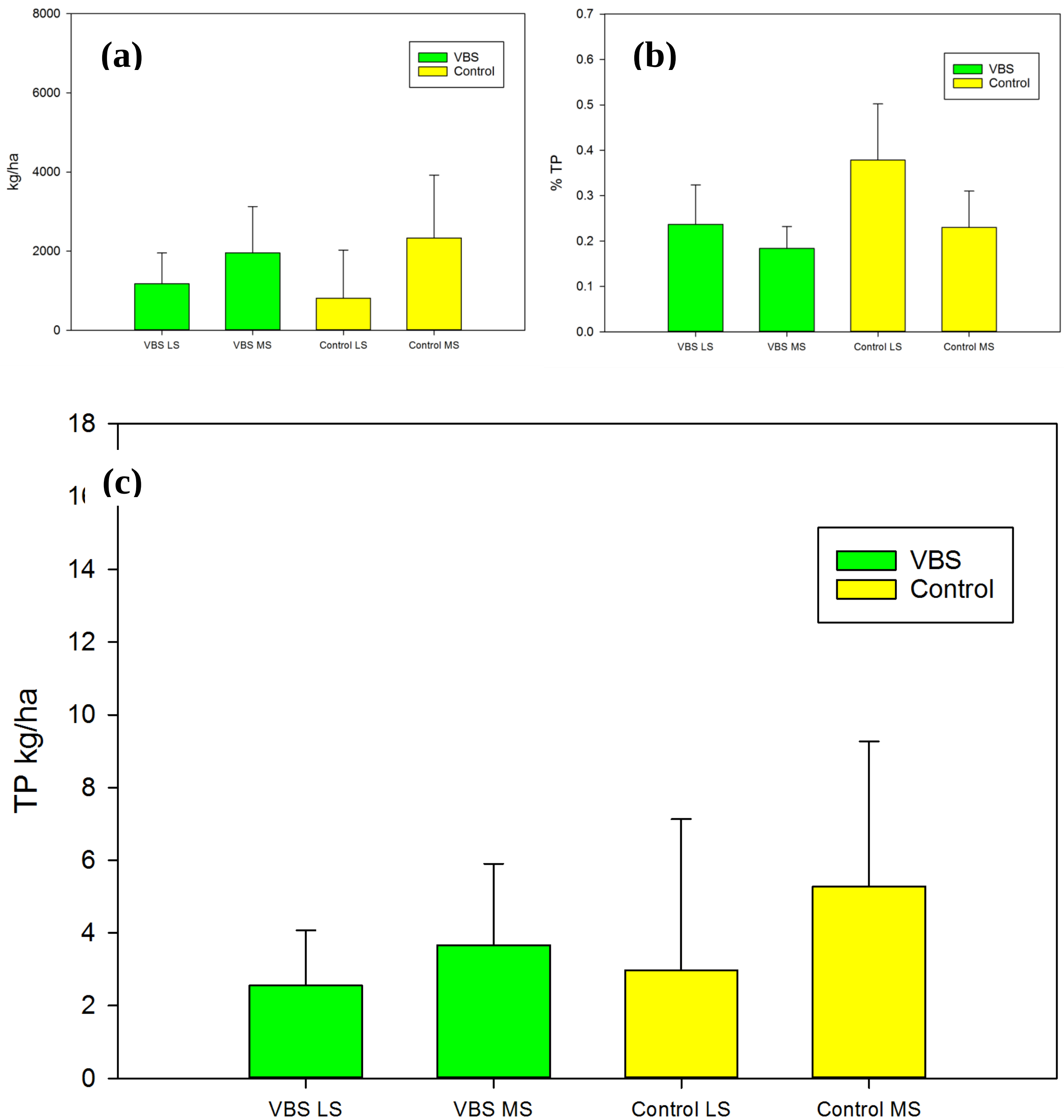

Figure 3.13. Harvestable vegetation mass (a), percent TP content (b), and TP mass (c), by lower slope (LS) and mid slope (MS) zones in the vegetated buffer strip (VBS) and control plots in the summer of 2016

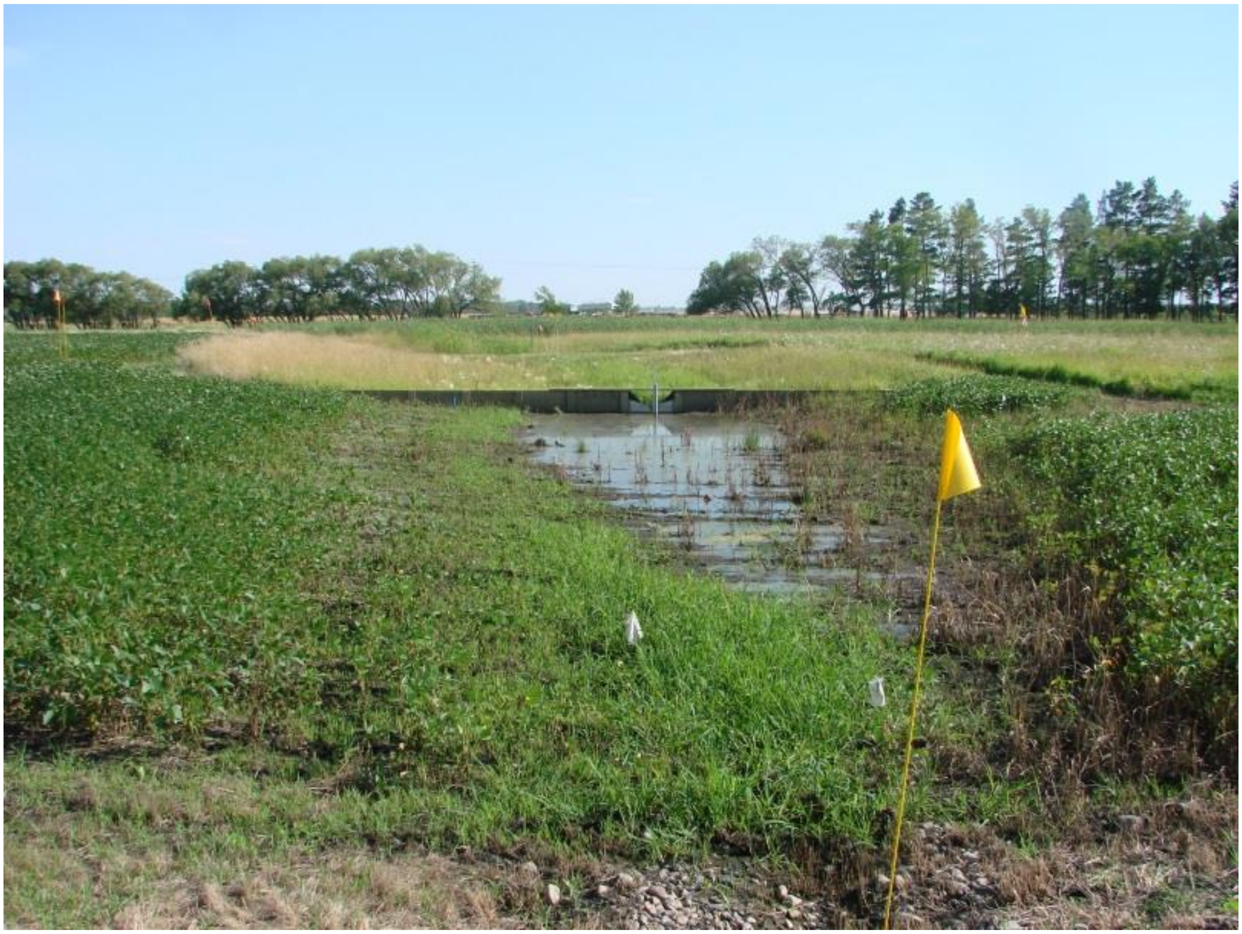

Figure 3.14. Plot C3 in summer of 2016 showing crop stress due to excess moisture conditions in the lower slope zone (photo is looking downslope)

3.3.2.2. Vegetative residue mass and phosphorus content patterns

The mass of vegetative residue, or plant material left above the soil surface after harvest, in VBS plots was higher than control strip plots, with a mean of 1,392 kg/ha and 984 kg/ha, respectively (Table 3.2). The percent TP content was similar in residues of VBS and control strip plots, with a mean of 0.13% and 0.12%, respectively. There was high variability in the percent TP content of the control strip plots, mainly due to the aforementioned difference in crop species (Figure 3.15). The mass of TP was higher in the VBS plots than the control strip plots, with a mean of 1.71 kg TP/ha and 1.25 kg TP/ha, respectively.

Table 3.2. Vegetative residue mass and TP content in the vegetated buffer strip (VBS) and control (C) plots in 2016

	n	Mean	Median	Std. Dev.
VBS Mass (kg/ha)	23	1,392	1,208	809
VBS % TP	23	0.13	0.13	0.03
VBS TP (kg/ha)	23	1.71	1.61	0.86
Control Mass (kg/ha)	21	984	1,016	631
Control % TP	21	0.12	0.13	0.07
Control TP mass (kg/ha)	21	1.25	0.88	1.21

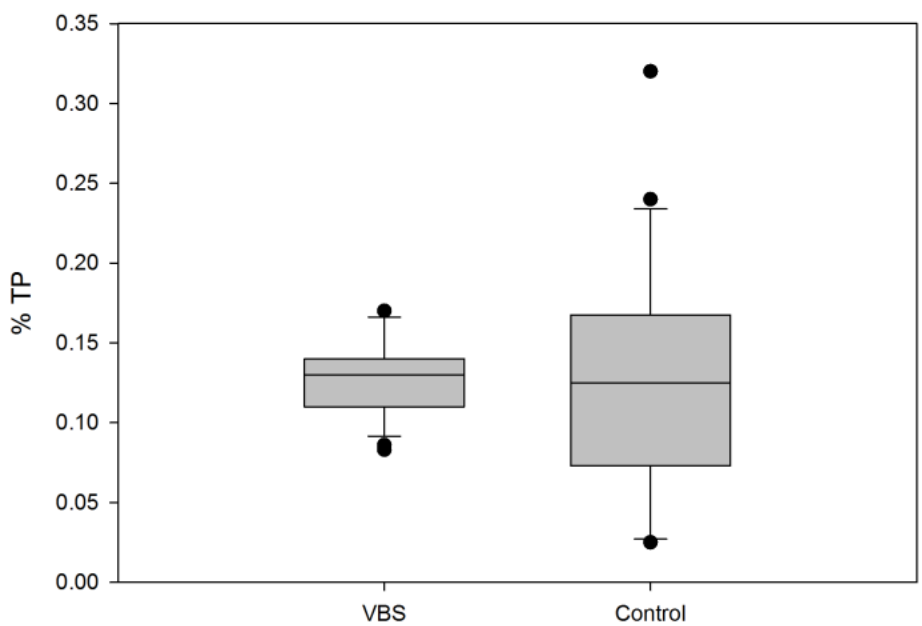

Figure 3.15. Vegetative residue percent TP content in VBS and controls (all data)

The mean vegetative residue mass, percent TP content, and TP mass for each plot is shown in Figure 3.16. Plot VBS3 had the highest mean mass of vegetative residue at 1,798 kg/ha, while plot C3 (soybean residue) had the lowest at 661 kg/ha. Again it should be noted that there was considerable variability in the data, especially in the control strip plots due to crop differences such as soybean, which is a low residue producing crop. Plot C1 (canola residue) had the highest mean percent TP content at 0.16% while plot C3 (soybean residue) had the lowest at 0.085%. The mean percent TP content in the VBS plots ranged from 0.11% to 0.14%. The mean mass of TP in the vegetative residues was highest in plot C1 (canola residue) at 2.1 kg TP/ha while C3 (soybean residue) was the lowest at 0.61 kg TP/ha. The mean mass of TP in the VBS plots ranged from 1.16 kg TP/ha in VBS2 to 2.02 kg TP/ha in VBS3. Plot VBS3 was one of the wetter VBS sites. This plot became very well established with thick, dense moisture-tolerant vegetation by the end of the growing season in 2016. This explains why it had higher amounts of residue, over twice as much as plot VBS2.

3.3.2.3. Temporal patterns in vegetative residue phosphorus mass

The comparison between the vegetative residue TP in the fall to the amount remaining the following spring is a useful measure for estimating the amount lost due to the fall senescence and plant decay during the over wintering period. This time period is critical for plant tissue decomposition, mainly due to freezing, thawing, and snowmelt processes that are common in cold climates during this period.

Eqn 3.1: fall TP mass (kg TP/ha) – spring TP mass (kg TP/ha) = mass TP lost from fall to spring (kg TP/ha).

The mass of TP in vegetative residue dropped substantially in the control strip plots from a mean of 1.93 kg TP/ha in the fall of 2016 to 0.76 kg TP/ha in the spring of 2017 (Figure 3.17). This represents a loss of 1.17 kg TP/ha, or a 61% decrease. Due to the fact that the VBS strips had started to grow at the time of the sampling in the spring of 2017, the data suggests an increase in the mass of TP in the vegetative residues in the VBS plots from the fall to the spring (from 1.44 kg TP/ha in the fall to 1.86 kg TP/ha). Although an increase in mass of TP in the residues is not an accurate representation of the over wintering processes, it does suggest that a significant reduction, such as that observed in the control strip plots, is not as likely in the VBS plots.

To further examine the influence of crop type, the control strip plots were broken down by crop type; i.e. canola and soybeans (Figure 3.18). The mean TP loss from fall to spring from all three VBS plots was -0.42 kg TP/ha (i.e. an increase), while the mean loss for the three control strip plots was 1.17 kg TP/ha. The mean loss from the two canola plots (C1 and C2) was 1.72 kg TP/ha, and from the soybean plot (C3) was 0.07 kg TP/ha.

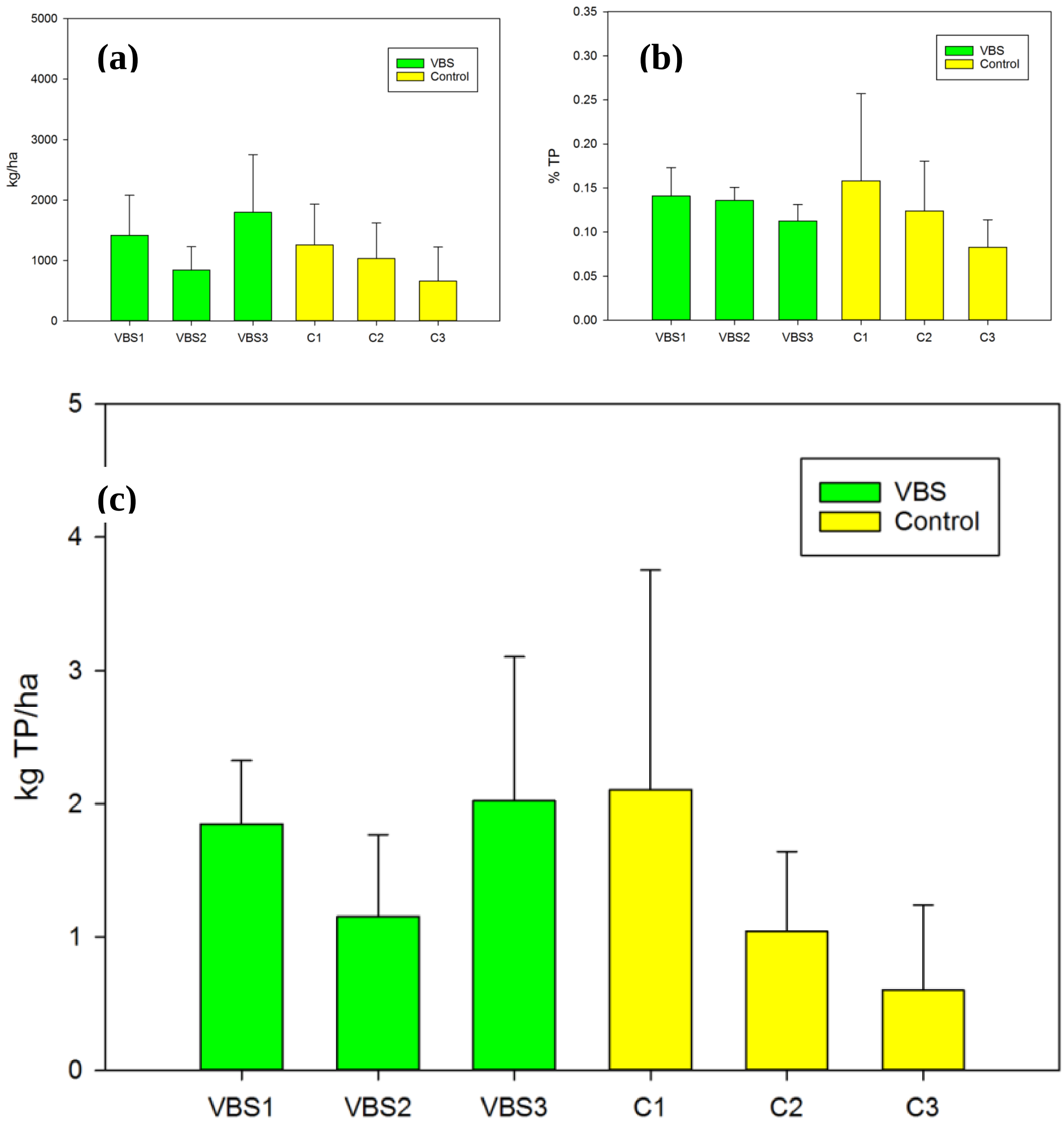

Figure 3.16. Vegetative residue mass (a), percent TP content (b), and TP mass (c), in each vegetated buffer strip (VBS) and control (C) plots in 2016

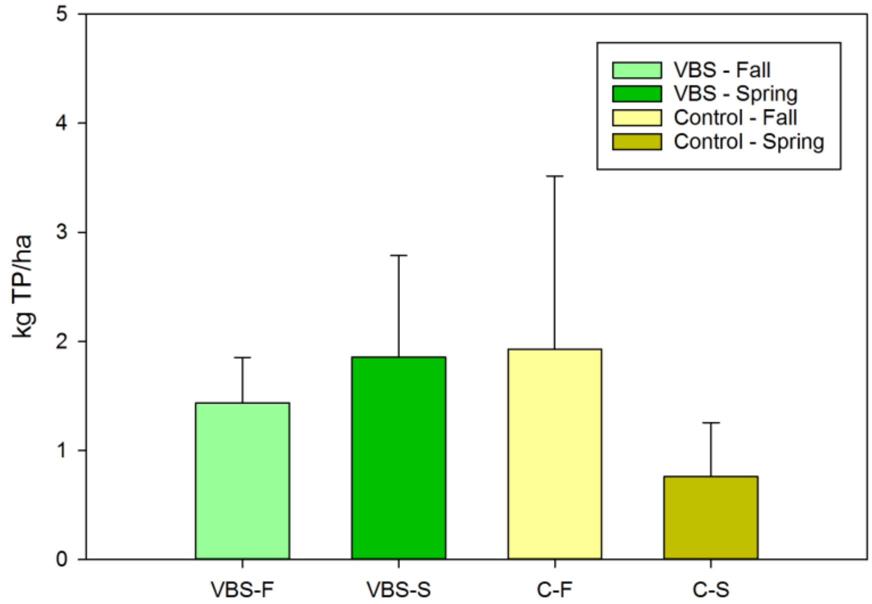

Figure 3.17. Vegetation residue mass of TP in vegetated buffer strip (VBS) and control (C) plots in fall (F) 2016 and spring (S) 2017

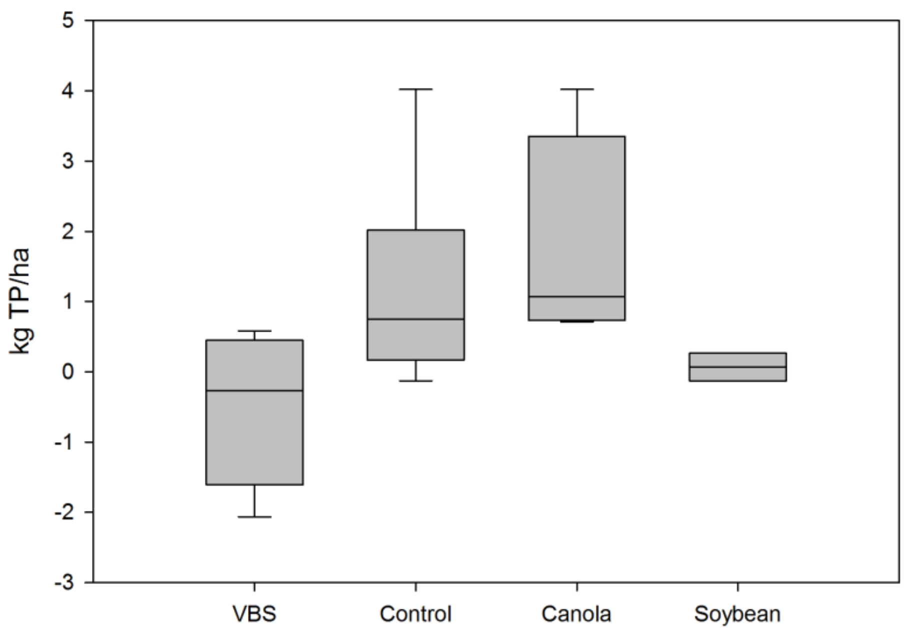

Figure 3.18. Vegetation residue TP loss from fall 2016 to spring 2017 in vegetated buffer strip (VBS) and control strip plots. Control strip plots are further broken down by crop residue type (canola and soybean).

3.3.2.4. Spatio-temporal patterns in vegetative residue phosphorus mass

Compared to the fall of 2016, the TP in the vegetative residues of the VBS sites in both the LS and MS zones increased in the spring of 2017. As stated previously, this is likely due to the fact the vegetation in these zones had already started to grow and accumulate additional mass and nutrients at the time of sampling. The MS zones in the VBS increased more than the lower zones, with mean increases of 37.1% and 15.6% more TP in their vegetative residues respectively (Figure 3.19). This indicates the MS zones may have dried and warmed and started growing more rapidly than the LS zones that were covered with snow, ice and water longer in the spring. Within the control strip plots, the TP in vegetative residues in the LS zones decreased considerably more than the MS zones, a decrease of 78.1% and 41.9%, respectively. This represents a substantial potential for P loss over this time period, especially in those LS zones that are exposed to more overland flow. The exposure to more snow, ice and snowmelt runoff and the resulting release of P may help explain some of the declines in TP in the vegetative residues in these zones. It is also important to note that cultivation causes crop residues to become more exposed and detached from the soil. This can lead to more vegetative residue getting washed away with runoff in the control strip plots than in the VBS plots that are not subjected to cultivation and where residues are more likely to be bound to the soil.

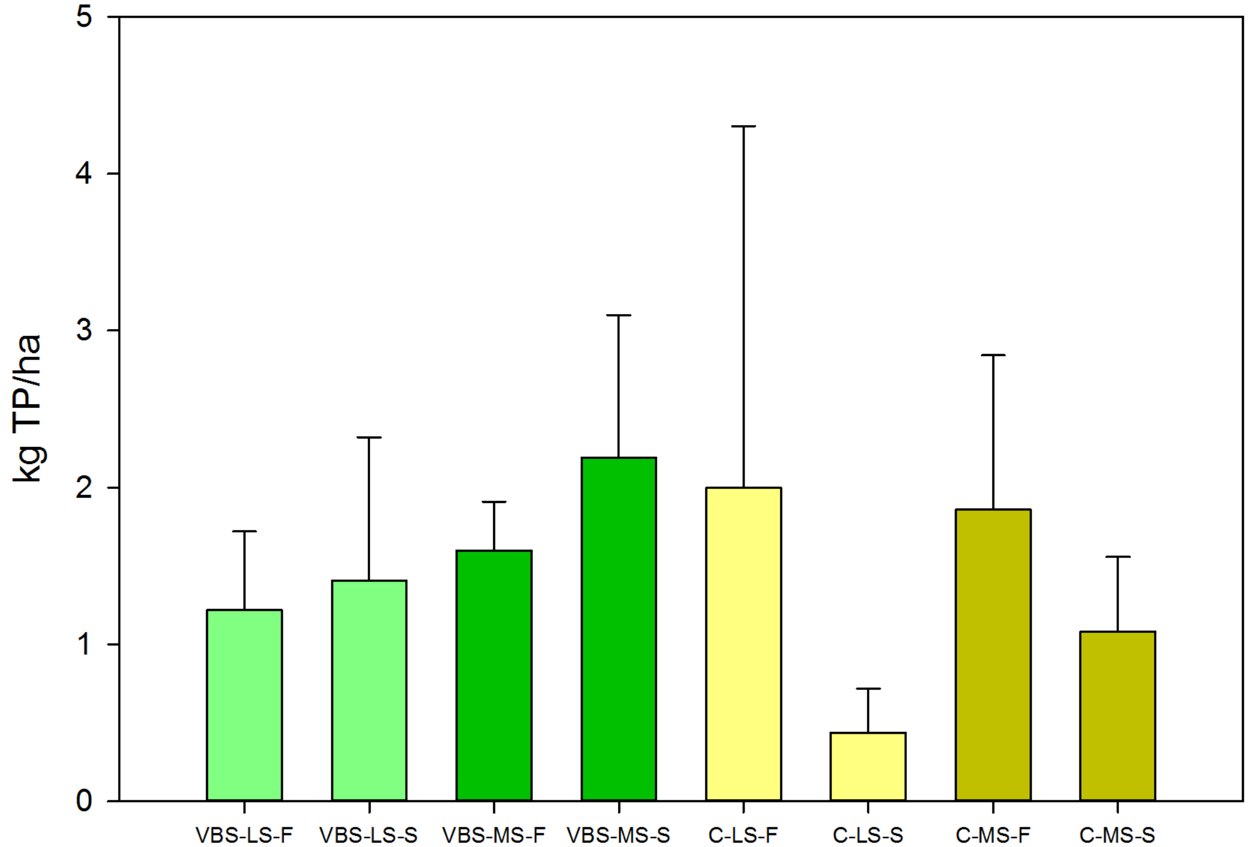

Figure 3.19. Vegetative residue TP in vegetated buffer strip (VBS) and control (C) plots by slope position [lower slope (LS) and mid-slope (MS)] and season [fall 2016 (F) and spring 2017 (S)].

3.3.2.5. Temporal patterns in vegetative residue phosphorus content

The content of TP in vegetative residues (i.e. expressed as a percentage of residue mass) for the different plots revealed that canola was the highest, followed by the grasses and forbs of the VBS plots, and then soybeans at 0.14%, 0.13%, and 0.08% respectively. The vegetative residues were sampled in the fall and again in the following spring, allowing an investigation of change in TP content during the critical fall, winter and snowmelt period. The TP content of the vegetative residues were substantially lower in the spring than the fall for all plots (Figure 3.20).

The canola plots showed the largest decline from a mean of 0.19% in the fall to 0.10% in the spring, a 49.7% decrease. The decreases in mean percent TP content in the VBS and soybean plot vegetative residues were less substantial, 9.0% and 3.5% decreases respectively.

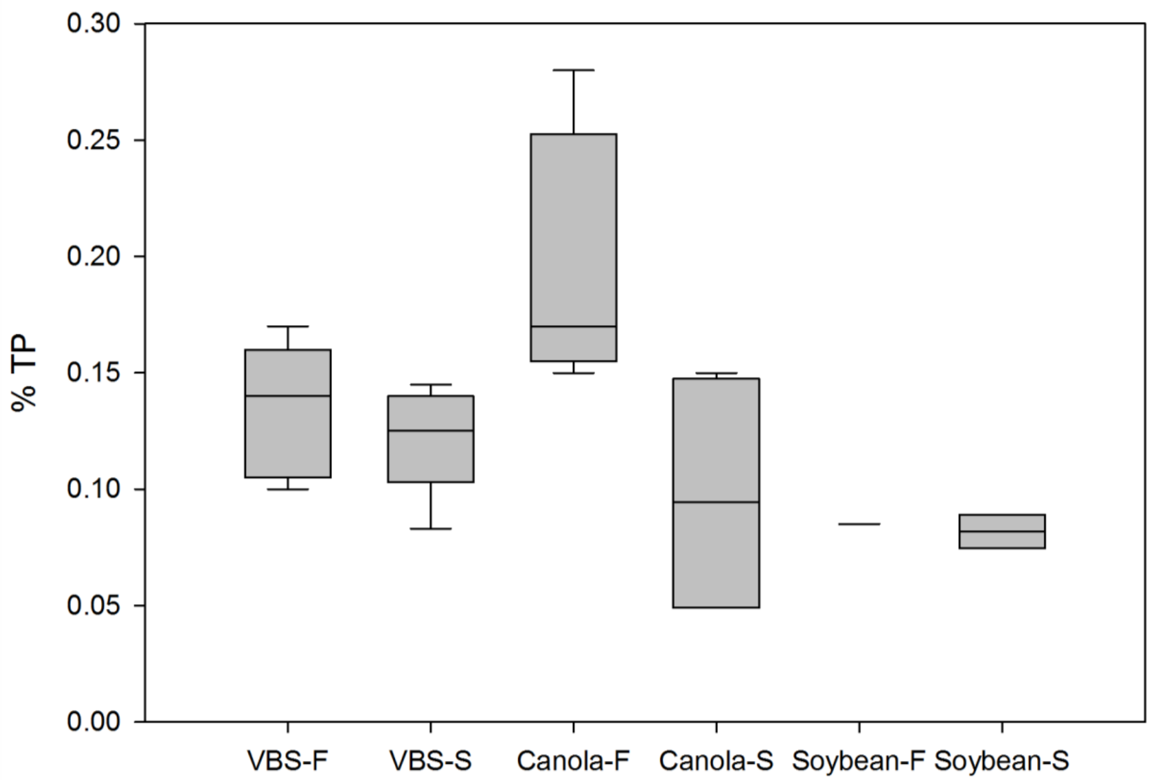

Figure 3.20. Total phosphorus content of vegetative buffer strip (VBS) plots, canola plots, and the soybean plot in fall (F) and spring (S)

3.4. Discussion

Although it is difficult to determine trends from a study of short duration (i.e. less than 2 years) like this one, there is evidence of patterns or possibly trends in soil P levels within the VBS and control strip plots. Although not statistically different, soil P, measured as Olsen P in this study, was higher in the control strip plots than the VBS plots. This can be attributed to the common agricultural practice of fertilizer P addition to the control strip plots intended to maximize productivity and meet crop uptake requirements. For all plots (VBS and controls), soil P levels were higher in the MS zones than the LS zones, an indication of potential loss of P to runoff or leaching in the LS zones.

Seasonally, soil P levels were higher in the spring than the subsequent fall in both VBS and control strip plots. This is likely due to the plants removing P from the soil over the growing season. However, the higher soil P in VBS plots in the spring is more difficult to explain because there is no fertilizer P added in the fall. Because of the lower slope position of the VBS sites, it is likely that nutrients are being delivered to these zones with snowmelt runoff from upslope areas. Another possible explanation is that decomposing vegetation releases P to the soils of the VBS in late fall after soil samples were collected or in the spring once the soils have thawed but prior to sampling. Soil P generally appears to be increasing in both the VBS and control strip plots over time, although the difference is not statistically different and to date only two time periods have been compared (spring of 2016 and spring of 2017). An increase in soil P in VBS plots has been reported in other studies in this region (Sheppard et al., 2006; Habibiandehkordi et al., 2017). An accumulation of P in the control strip plots was unexpected, but may be an artifact of their landscape position. Wilson et al. (2016) found that low lying areas with a high wetness index had the highest Olsen P levels at the 0-15 cm depth. The control strip plots in this study were in lower areas where overland flow accumulates and that were frequently wet. The moisture stress on the crops in these conditions can decrease productivity and lead to crop P removal rates that are lower than fertilizer inputs, resulting in a P surplus in the soil (Ali et al., 2017).

Although not statistically significant, soil P levels increased more substantially in the LS-D zones (5-20 m into the plots) than the LS-U zones (0-5 m into the plots). This phenomenon was evident in both the VBS and control strip plots. This is likely due to deposition and adsorption in the soils within these areas, exacerbated by the frequent ponding that occurred due to the position of the weirs and berms at the downstream edge of each plot.

Plant biomass, in the form of harvestable vegetation and residues, in the plots in this study contained a substantial amount of P. The harvestable material in the VBS plots contained a mean of 3.33 kg/ha of TP, while the harvestable plant material in the control strip plots contained a mean of 5.07 kg/ha of TP. In the case of the control strip plots, only a fraction of this was actually removed by harvesting just the grain portion. The post-harvest vegetative residues in the fall also contained significant amounts of P. The VBS and control strip plant residues in the fall contained 1.43 kg/ha and 1.93 kg/ha of TP, respectively. The decrease in vegetative residue P from fall to spring in the control strip plots was substantial, a loss of 1.17 kg TP/ha or a 61% decrease. The loss of P from control strip plot residues was more pronounced in the LS zones, a decrease of 1.56 kg TP/ha or a 78% loss. These values are considerable when compared to annual runoff export coefficients from cropland in this region, that range from 0.30 to 0.38 kg TP/ha/year according to a study by Yang et al. (2014).

Although this study did not show that VBS residues experienced a loss in mass of P from fall to spring, the content of P in VBS plant material declined by 9.0% over this period which can help explain why a VBS can be a source of P to runoff outside the growing season. Although VBS residues are a potentially significant source of P to runoff, the results of this study suggest some annual crop residues may be a much larger source. In terms of content, or percent TP in the residual plant material, the canola residues in this study lost 49.7% of their TP during the fall to spring period that included the hydrologically critical snowmelt period.

3.4.1. Study Limitations

The most significant limitation in this study was its short duration. Analysis of trends requires multiple measurements over long periods of time. This study relied on measurements from only two years of data either comparing the spring of 2016 to the spring of 2017, or the fall of 2016 to the spring of 2017. A comparison of multiple years of data under different conditions would be required to confirm some of the early patterns and trends in soil and vegetation P that appear to be emerging in the relatively young VBS plots in this study.

The age of the VBS plots in this study is also a limitation. The data in this study were collected within 2 years of first seeding the VBS plots, a very limited time to allow the vegetation to fully establish and function. Significant changes in soil P have been reported to take a long time, possibly more than a decade (McCollum, 1991; Dosskey et al., 2007; Meals et al., 2010; Liu et al., 2014).

The timing of vegetative residue sampling in the VBS was also problematic. In order to assess changes in the amount of P in the residues from the time of senescence in the fall to after snowmelt, spring sampling needs to occur prior to regrowth to avoid collecting this new plant material. This unintentional sampling of the new growth would lead to erroneously overestimating the mass of spring samples, and thereby introducing error. There is a relatively short period of time in the spring after snowmelt when the residues can be collected and the plants are not growing. Spring sampling in this study was too late and some regrowth had started to occur in VBS plots, affecting the mass and amount of P in the samples.

Cessation of tillage and establishment of perennial grasses and forage crops results in stratification of soil P and elevated levels near the surface (Liu et al., 2014). During this study, soil samples of the more shallow depths (0-5 cm) were not collected until the spring of 2017. Therefore, analysis of changes in soil P over time could only be performed for the 0-15 cm depth that was collected consistently across the study period. This would not account for potentially more significant and important changes nearer the soil surface that are likely to have a greater influence on the P content in runoff due to the frequent soil–water interactions in this shallow zone.

This study utilized weirs and berms to facilitate overland flow monitoring and sample collection, as outlined in Chapter 2. These structures caused ponding in the downstream portions of both the control and VBS plots. This may have led to unusually high levels of deposition, infiltration and soil P accumulation in these areas within the plots.

3.5. Conclusions

3.5.1. Research Questions

3.5.1.1. Do newly established VBS accumulate P in the soil over time? If so, where?

Although there is an increase in the mean Olsen P in the soil at 0-15 cm depth in the three 20 m VBS plots over the first two years of the study, there is no statistical difference between spring 2016 and spring 2017. More data are required to see if there is a statistical trend in soil P levels within the VBS. Increases in mean Olsen P in the soil were more pronounced in the LS zones than the MS zones, although again this difference was not statistically significant. The largest increases in mean soil Olsen P in the first year were in the LS-D zones (5-20 m into the VBS). Although this contradicts other studies (e.g. Sheppard et al., 2006; Habibiandehkordi et al., 2017) that found more accumulation in the leading edge (0-5 m into the VBS), the accumulation in this case may be caused by deposition due to the weirs and berms at the downstream end of the plots.

3.5.1.2. Do annual crop strips in a concentrated overland flow path accumulate P in the soil? If so, where?

Although there is an increase in mean Olsen P in the soil at 0-15 cm depth in the three 20 m annually cropped control strip plots over the first two years of the study, there is no statistical difference between spring 2016 and spring 2017. Similar to the VBS plots, the LS-D zones (5-20 m into the control) experienced the highest increase in mean soil Olsen P, although again not statistically significant. Again, this is attributable to the ponding and deposition caused by the downstream weirs at the outflow points of the control strip plots. Moisture stress on the crops in these zones contributed to a decrease in P uptake and likely led to an annual surplus of soil P due to fertilization.

3.5.1.3. Does vegetation harvesting remove significant amounts of P from a VBS?

Harvesting vegetation removed a mean amount of 3.33 kg/ha of TP from VBS sites in this study. Based on the estimated yield of P from cropland in this area at about 0.3-0.4 kg TP/ha/yr (Yang et al., 2014), this would be a significant amount, about 10 times the annual export rate from cropland in this region. More so, the removal of the vegetation and its associated P is likely to contribute to reducing soil P levels over time. Soil P levels and the degree of saturation is an important factor in determining VBS P retention capacity.

3.5.1.4. Do vegetative residues represent a significant source of P to surface runoff in a VBS?

Although not as substantial as the harvestable plant material, VBS residues in this study contained a significant amount of P (1.71 kg TP/ha). This is about six times the estimated annual P export rates from cropland in this region (Yang et al., 2014). Although considerable, TP levels in VBS residues are less than the canola residues that contained a mean of 2.1 kg TP/ha. Both VBS and annual crop residues exhibited a decrease in P content (%TP) from the fall to spring period, representing a potential source of P to runoff, especially during snowmelt. Canola residue P content in the control strip plots decreased the most (49.7%), followed by the VBS residues (9.0%), then soybean residues (3.5%). This suggests that plant species is an important factor in determining the potential for vegetative residues to be a significant source of P to surface runoff in this region.

3.5.2. Management implications and future research

Although short in duration, and more data are required for statistical validation, this study supports the findings of other studies that there is the potential for soil P accumulation in VBS sites. This corroborates the theories that, over time, VBS soils may lose or have diminished capacity to retain P from runoff as they could become P-saturated. Methods to remove or "mine" P from the VBS soils to reduce P surpluses should be employed and studied. Along with vegetation harvesting, this could include periodic over-seeding and nitrogen fertilizer application to ensure thick and dense vegetation in the VBS to maximize P uptake by the plants. Trade-offs due to these practices such as reduced erosion prevention and sediment trapping potential after harvest, and increased nitrogen losses to runoff due to fertilizer application, would need to be considered. Issues that require further research, include: (i) optimal times to fertilize and harvest; (ii) the number of times to harvest per year; and (iii) how much residual vegetation to leave in the fall. In order to optimize the timing of harvest, more research needs to be conducted in cold climates to determine when the different VBS plant species cease their uptake of P, and begin to senesce, decompose and ultimately release P. High-frequency harvestable VBS vegetation sampling and water extractable P analyses over multiple seasons, over multiple years and with different plant species should be included in future experiments in this region.

This research highlighted the importance of plant residues as a potential source of P to runoff in cold climates. This was particularly evident with canola, the most common crop in Manitoba in 2016 and 2017 (Manitoba Agriculture, 2018), that had higher P content than VBS residues in the fall and lost nearly half of its P content by the following spring. Plant residue studies that include different annual crops and VBS species should be conducted to further examine their potential to become sources of P to runoff in this region, especially during the post-harvest season in the fall and prior to plant emergence and regrowth in the spring.

4. Synthesis and Conclusions

4.1. Conclusions

The objective of this research was to assess the efficacy of vegetated buffer strips (VBS) to retain phosphorus (P) in cold climates. The research questions (Figure 1.1) and a brief summary of the results are presented in Table 4.1.

Table 4.1. Research question and results summary

Research Question	Chapter	Results Summary
Do vegetated buffer strips lower phosphorus concentrations in surface runoff in cold climates?	2	There was no statistical difference in the VBS mean inflow and outflow concentrations of TP or TDP. The VBS reduced mean TP concentrations in 14 of the 22 events during the study. The mean TP concentration for all plots for all events at the VBS outflow was 11.4% lower than the VBS inflow (227.7 µg/L and 257.1 µg/L respectively).
How do annual crop strips compare to vegetated buffer strips for phosphorus concentration reduction in surface runoff?	2	Annual crop strips reduced mean TDP concentrations more than VBS plots. VBS plots reduced TP concentrations more than control strip plots. VBS plots were substantially better than annual crop strips for reducing TSS concentrations.
Do newly established VBS accumulate P in the soil over time?	3	There was no statistical difference in Olsen P in the VBS soils over the first two years of the study. Mean Olsen P in the VBS plots increased from 16.9 mg/kg in the spring of 2016 to 20.5 mg/kg in the spring of 2017, an increase of 21.3%.
Do annual crop strips in a concentrated overland flow path accumulate P in the soil?	3	There was no statistical difference in Olsen P in the control strip soils over the first two years of the study. Mean Olsen P in the annual crop strip plots remained relatively constant, 23.1 mg/kg in spring of 2016 and 23.5 mg/kg in spring of 2017, a difference of only 1.7%.
Does vegetation harvesting remove significant amounts of P from a VBS?	3	Harvesting vegetation removed a mean amount of 3.33 kg/ha/year of TP from VBS sites.
Do vegetative residues represent a significant source of P to surface runoff in a VBS?	3	Vegetated buffer strip residues contained a mean of 1.71 kg TP/ha. Compared to annual estimates of P yield from farmland of 0.2 – 0.3 kg TP/ha/year, this is a potentially significant source.

To better understand the source and fate of P within VBS, levels of P in the vegetation and soil were tracked throughout the study. Due to the extreme differences in the physical and biogeochemical conditions within a VBS during the different seasons, it was important to collect data at multiple times throughout the year and assess the performance and condition of the VBS seasonally. In order to compare the impact of establishing new VBS, this study included a comparison of the VBS to annual crop strips as controls. During the relatively short duration of this study (less than 2 years of field data collection), there was no statistically supported evidence of P accumulation within the VBS soils.

The study, which included analysis of runoff event water samples between the fall of 2015 and the spring of 2017, showed an inconsistency in VBS performance for reducing P concentrations in runoff. Overall, there was no statistical difference in the performance of the VBS sites and the controls for reducing P concentrations. This supported the findings of other researchers that suggested VBS are not always effective at retaining P, and can even increase levels of P especially outside the growing season (Sheppard et al., 2006, 2012; Habibiandehkordi et al., 2017). The current research points to the fall period, when VBS vegetation senesces and decomposes, as a critical time when a VBS subjected to runoff may release P and become a source instead of a sink.

There was a substantial amount of P found in the vegetation and residues of both the VBS and control strip plots. There was a considerable decrease in the content of P in the vegetative residues in the spring after going through the overwintering and snowmelt period, suggesting P was released during this period. This corroborates previous research at this site that found VBS vegetation to be a significant pool of P, and that overwintering and freeze thaw cycles, common during the snowmelt period, result in significant releases of P to water (Kieta, 2017).

Although certainly not exhaustive at only 18 months in duration, especially as it pertains to soil chemical changes that can be very slow, there was evidence of P retention in VBS soils over the study period. Mean Olsen P in the VBS plots increased from 16.9 mg/kg in the spring of 2016 to 20.5 mg/kg in the spring of 2017, an increase of 21.3%. Even though the results must be considered preliminary in this case, it does support previous findings where VBS soils become enriched with P over time (Cooper et al., 1995; Sheppard et al., 2006). This is an important finding as soil P levels can exert a significant influence on the capacity for P to be retained within a VBS, and continued accumulation can lead to P saturation, and ultimately the release of P to overland flow. These conditions could cause VBS sites to increase P concentrations in runoff rather than decreasing them.

Due to frequent wet conditions, the VBS vegetation as it establishes is generally adapted to moist conditions, more so than the monoculture annual crop systems. This is especially true for crops that are less tolerant of prolonged wet periods like soybeans and canola. This was evident in this study when comparing the VBS3 plot to the adjacent control strip plot C3 during the growing season of 2016. The VBS plot had thick, dense vegetation while the control strip soybean crop was mostly dead or sparse in the low lying areas, creating a lot of bare ground where the overland flow occurred. The poor crop growth in these low-lying areas would not only cause increased amounts of exposed soil and erosion but the reduced plant uptake of nutrients could also lead to a build-up in the soils over time, especially if fertilizer is applied to these areas. Increased soil P levels are likely to result in higher P levels in the runoff.

4.2. Study limitations

A major limitation of this study was related to the age of the VBS plots. The VBS plots were very young, seeded in the spring of 2015 and not nearly mature, with relatively sparse vegetative cover in each of the plots, at the time the study commenced later that fall. Although they became better established with increased vegetation density in the second year of the study, they were still immature sites. The characteristics that make a VBS site differ from an annual crop and increase its capacity for P retention can take considerable time to develop, possibly even more than a decade (McCollum, 1991; Dosskey et al., 2007; Meals et al., 2010; Liu et al., 2014). Some key VBS characteristics that are likely to develop more fully over time include increased vegetation stand density and stem thickness, and soil macropore development. These factors can have a significant influence on sedimentation and infiltration rates, both reported to be critical to P retention in VBS sites (Syversen, 2005; Dabney et al., 2006; Sheppard et al., 2006; Hoffmann et al., 2009; Stewart et al., 2011).

A longer study period including additional sites with different landscape characteristics such as soil type and slope, would improve the statistical analyses and expand the relevance of the findings to a broader region. This study was conducted on loam soils, consisting mainly of Hochfeld, Chortitz, Graysville, and Neuenberg soil series, in a low relief landscape. The inclusion of additional sites that are considered to be legacy P sources, or those that have experienced long term P surpluses and accumulation over time resulting in abnormally high soil P levels, would be valuable as they are prone to high runoff P levels. Mature VBS sites, where the vegetation is harvested and removed, may serve to assimilate and reduce soil P levels and mitigate the legacy P issue over time. With a longer duration study spanning many years, this mining of soil P may significantly increase the P retention capacity of the VBS over the long term.

A longer study period may help to fill gaps in the types of events that were lacking as part of this study. Although VBS sites appeared to increase P concentrations in runoff in the fall period, and this is likely explained by vegetation senescence and release of P, all events during this time period were artificially induced. These artificial events were characterized by very low P concentrations in the VBS inflow and were strongly dominated by dissolved forms of P. These factors may have led to an exaggeration of the poor performance of the VBS during these types of events. Natural rainfall events during the fall would help to address this issue and determine if the VBS performance during this time period was underestimated.

Although some variability between VBS plots is expected, it should be noted that one of the sites in this study had substantially higher soil P levels throughout the experiment than the others (i.e. plots VBS1 and C1). This site also had the most runoff events and water samples collected because it did not rely on the overflow from a retention pond like the other two sites. This may have resulted in an increased emphasis on this site during this study and the potentially adverse condition of its high soil P levels negatively affecting its performance and the assessment of the VBS plots overall.

Vegetated buffers are reported to perform better under conditions of shallow diffuse flow rather than deep, concentrated flow. In order to collect water samples and utilize automated sampling equipment, this experiment used weirs and pipes to concentrate flow and raise water levels to facilitate the sample collection. This may have reduced the efficacy of the VBS plots to retain P during this study when compared to the natural condition that would have been more shallow and diffuse. The level topography was also problematic, especially during extremely high flow events. The weirs, pipes and drainage channels often restricted flow during high flow conditions, causing backwater effects at upstream locations and making accurate flow rate calculations difficult or impossible.

4.3. Implications for designing and managing vegetated buffers trips in cold climates

Some of the plots in this study had high levels of P at the soil surface at the time of VBS establishment. Deep ploughing or tillage to incorporate some of the P into lower depths prior to VBS establishment would reduce the potential for P transfer from VBS soils to overland flow. The harvest and removal of the VBS vegetation may also contribute to a gradual decrease of the soil P levels through vegetative uptake of soil nutrients over time. The practice of removing VBS vegetation will also benefit the performance of the VBS by reducing the amount of vegetative residue and associated P that could be released to runoff as the plant material decays in the fall and winter. Because nitrogen is often a limiting nutrient for terrestrial plants, nitrogen fertilizer application to VBS sites is likely to increase VBS vegetation health and stand density, thereby increasing P uptake from the soil. Although nitrogen fertilization may result in increased P uptake and retention within the VBS, the temporarily higher levels of nitrogen in the soil could lead to an increased risk of nitrate losses in the runoff or leaching to groundwater. However, sound nutrient management techniques, such as optimal fertilizer timing and split applications, could mitigate these risks.

A major limitation for VBS performance for P retention occurs when the sites are inundated with deep, concentrated flow. New designs that convert the channelized concentrated flow to diffuse shallow would help alleviate this problem. This could be accomplished by directing the channelized flow over an embankment and using level-spreaders to disperse the runoff over a wider area and then down a gently sloping (<10% slope) VBS, thereby increasing the surface area for overland flow and reducing runoff depths. This would increase the cost of implementing VBS due to earthwork and construction related expenses, but it could dramatically increase the P retention capacity of the sites. If the site were high in soil P prior to construction, using topsoil that is lower in P for the VBS would address this issue but could also increase costs. The removal and replacement of topsoil for this reason in wetland restoration projects has been recommended by other researchers (e.g. Pfeifer-Meister et al., 2012).

This study supports the findings that VBS do not perform uniformly across seasons. If some control over flow through the VBS is possible, as was the case for two of the VBS plots in this study that were downstream of retention ponds, then minimizing flow outside the growing season would reduce the potential for additional P loss due to vegetative decay. Designing or managing flow through a VBS to increase retention time during the growing season would increase infiltration rates as well. However, in the managed flow sites it would be detrimental for P retention if water were to pond long enough to create anaerobic conditions increasing the potential for P release from the flooded soils. Long periods of inundation could also kill the VBS vegetation thereby reducing its filtering and nutrient assimilation capacity. These situations should be avoided if possible in managed, or flow controlled, VBS sites.

4.4. Implications for future cold climate vegetated buffer strip research

The findings of this study support the contention that VBS sites, with traditional designs and management schemes, perform well during growing season rain events but may have little or even negative effects on P retention outside that season. At present, the majority of runoff in this region tends to be generated from snowmelt in the spring. However, climate change may lead to alterations in the hydrology of this region in the future. Some studies predict earlier and more frequent melts during the winter and early spring, leading to less substantial events in the mid to late spring period (Gan, 2000). Some climate change models point to higher frequencies of large convective storms in the summer and more total runoff than at present (Dibike et al., 2012; Shrethsa et al., 2012). Longer term studies that include more data from multiple types of events including spring snowmelt and intense summer storms, or utilize high intensity rainfall simulations, would help improve the understanding of how VBS perform under these varying conditions. These field studies could be supplemented by modelling approaches to simulate and predict the effects of VBS under changing climatic conditions such as a higher frequency of convective summer storms and less runoff occurring during spring snowmelt conditions.

This study revealed considerable variability among the sites with respect to inflow concentrations of P and TSS, soil P levels, and the amount of P in growing and decaying vegetation. This variability included substantial changes in inflow concentrations both within events and between events. For example, in many events that occurred while there was considerable bare ground in the source areas, samples tended to be more turbid and sediment laden early in the event and lessened as the event progressed. This phenomenon was more evident during early season high-intensity rain storms. There was also evidence of lower P in inflow samples at the latter stages of events. Other studies have also reported on the importance of the timing of sample collection and a comprehensive strategy for data collection at VBS sites to minimize error especially with respect to dissolved and particulate fractions of P (Ulen et al., 2015). This emphasizes the need for multiple samples to be collected representing as many of the event stages as possible and supports similar recommendations from previous studies (Casssidy and Jorden, 2011; Ulen et al., 2012b). Samples representing the rising limb, peak, and falling limb portions of the hydrograph would be ideal. Further study into these important and dynamic factors should be conducted to determine how changes in these hydrologic conditions may influence VBS performance in cold climates.

Further research on the relationship between near surface soil P and VBS inflow concentrations are required to further explore the impact of high soil P levels on runoff P. This could help determine whether there is a threshold inflow P concentration under certain soil P levels, where a VBS will retain P from runoff or release it from the soil. Inclusion of additional site events to a study under varied soil P and inflow P concentrations may help predict the retention capacity and performance of different VBS sites. This research could also assist with selection and management of VBS sites based on the characteristics of the soil and expected levels of P in the contributing runoff.

Future efforts to investigate the impact of VBS sites on reducing flow volumes would be an important contribution. Although challenging to collect accurate flow rates and volumes at the small scale sites in this study (i.e. only 20 m in length), it is important to determine whether a VBS will reduce flow volumes, as has been reported in many previous studies from warmer regions (e.g. Gitau et al., 2005; Duchemin and Hogue, 2009; Hernandez-Santana et al., 2013). Theoretically, a VBS may reduce runoff volumes over time through increased infiltration, but this process may be hampered by frozen conditions that are common in the late fall, winter and early spring in this region. Assessments of flow volume through a VBS in the different seasons would be a significant contribution to better understanding VBS performance and processes in cold climates. Due to the challenging nature of flow measurement at these sites (i.e. often inundated and submerged with floodwater from both upstream and downstream locations in the large events), soil infiltration experiments may be a viable substitute for direct flow measurements in future studies to determine VBS impacts on this hydrological process.

This study also revealed the importance of vegetation and plant residues as a substantial source of P to runoff in cold climates. There appears to be considerable variability in the P content of different vegetation types, especially among common commercial crops in this region (e.g. canola and soybeans). However, the precise timing and conditions likely to cause the release of this P is not yet well understood. Future studies that examine the changing content of P in plants at their different growth stages, from early season to senescence, and under different field conditions would help determine when they are most likely to be susceptible to release P to runoff. This would yield valuable insights into the optimal timing and frequency of vegetation harvesting in VBS sites to maximize their P uptake and minimize the P loss potential due to decomposition. Although there has been some recent research conducted on the relationship between soil P and vegetation P in this region (Kieta, 2017), this could be explored further under a variety of field conditions. There is evidence that high soil P concentrations result in increased, transient P levels in plant tissues, a process referred to as luxury P uptake, and may have implications on the potential for P release to surface runoff. Research into these processes and the conditions that lead to significant P losses from vegetation should be explored further in this region. Studies that investigate P content in vegetative material under a variety of field conditions, including different plant species, during different seasons, and exposed to varied soil P levels, should be pursued. These studies, augmented by water extractable P experiments from soils and plant tissues, could be used to predict the amount of P that would be released to runoff under these conditions as described above.

Finally, one of the significant limitations of this study design was that it induced increased runoff depths and concentrated flow conditions through the VBS sites. Future experimental designs could incorporate methods to minimize concentrated flow and convert it to more diffuse, shallow flow, conditions under which VBS have been reported to perform better for nutrient retention. These designs could include landscape modifications to spread the flow out over a wider area (i.e. level-spreaders) and then direct over wider gently sloping outflow areas. The impact of these designs on sediment trapping, infiltration, and soil and vegetation nutrient dynamics in cold climates should be explored.

4.5. Summary

Due to a variety of reasons, this study suggests that the typical implementation of VBS practices, including the establishment of grasses in concentrated flow paths without consideration for vegetation removal, may have limited effect on reducing P concentrations. This research contributes to the understanding of the factors that may result in poor VBS performance for P retention in cold climates, including the seasonal nature of VBS processes for P capture, the significant amount of P in plant tissues and the potential release after senescence. This should help guide future adaptations for VBS in these regions and develop experiments that test new and innovative designs to address the “short circuiting” of VBS functions due to concentrated flow, especially during large snowmelt events. Coupled with management practices that reduce losses from the dominant sources of P in cold climates, namely surface soils and vegetative residues, these new designs could lead to significant advancements for VBS performance for P retention in cold climates. Ultimately, the combination of these new designs and management approaches could become an integral part of scientifically supported strategies that effectively address the persistent problem of excessive P losses all too common in cold climate agricultural watersheds around the world.

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