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Phosphorus dynamics in vegetated buffer strips in cold climates: A review

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Abstract: The movement of excess phosphorus (P) into streams, rivers and lakes poses a significant threat to water quality and the health of aquatic ecosystems and thus P has been targeted for reduction. In landscapes dominated by agriculture, P is primarily transported through non-point sources which a number of best management practices aim to target. One such practice is vegetated buffer strips (VBS), which are designed to use dense vegetation above the surface and extensive root systems below the surface to reduce runoff velocity, trap sediments, increase infiltration, and increase plant uptake of nutrients. The effectiveness of VBS in reducing P concentrations has been studied and reviewed, but most studies have been undertaken in warm or temperate climates, where runoff is primarily driven through summer rainfall events, and when vegetation is actively growing. In cold climates, the majority of runoff occurs during the snowmelt period when vegetation is not actively taking up nutrients, has been flattened by snow and ice over the winter period, and when soils are frozen. These conditions hinder the ability for VBS to work as designed. Additionally, frozen vegetation can release P after undergoing freeze-thaw cycles (FTCs). Thus, this review aimed to: i) summarize research designed to determine the effectiveness of VBS to reduce P transport undertaken in cold climates; ii) collate research on the potential for vegetation to release P after undergoing FTCs; and iii) identify research gaps to be addressed in determining VBS effectiveness in cold climates. Cold climate VBS implemented in Canada, the northern United States, and northern Europe have shown P removal efficiencies ranging from -36% to +89%, a range that pinpoints the uncertainty surrounding the use of VBS in these landscapes. However, there is consensus in research globally that vegetation does release P after undergoing FTCs, though P concentrations from different species vary across studies. The design and management of VBS in cold climates requires careful consideration and may not always be the best management strategy to reduce P transport. Future research should be
undertaken at a larger scale in natural systems and focus on VBS design and management strategies.

**Keywords**: phosphorus; vegetated buffer strips; cold climates; nutrient retention; watershed management; freeze-thaw cycles

### 1. Introduction

The transport of excess nutrients, namely phosphorus (P) and nitrogen, from tributaries to lakes pose a significant threat to water quality and to the health of humans and aquatic organisms (Schindler 1971, 1974; Little 2006; Armstrong and McCullough 2011; Kotak et al. 2011). The limiting nutrient in these freshwater systems is usually P and thus P has been targeted globally in scientific and policy research for reduction within lakes and tributaries throughout Europe (e.g., Schauser and Chorus 2007), North America (e.g., Schindler 1974; Levesque and Page 2011; Schindler et al. 2012), and China (e.g., Tong et al. 2017). While both point and non-point sources of P can impact water quality, non-point sources are much more difficult to manage and have become the more influential contributor of P in many aquatic systems (Sharpley 1995). Non-point sources are more difficult to manage than point sources because they are dependent on the landscape and on environmental conditions. In landscapes dominated by agriculture, non-point sources of P include synthetic fertilizer, manure, soils, and vegetation.

In an effort to reduce the transport of soil P from agricultural fields to surface water bodies, a number of beneficial management practices (BMPs) have been implemented to varying degrees of success. One of the most universally implemented BMPs is vegetated buffer strips, or buffers, which have become common and even mandatory (e.g., EU CAP 2009; State of Minnesota 2016) in agricultural landscapes across the globe. While ‘buffer’ is a term under which a variety of edge-of-field and in-field BMPs fall, for the purpose of this review, the terms buffer and
vegetated buffer strip (VBS), unless otherwise noted, are used following a modified definition from Fischer and Fischenich (2000). A linear band of permanent vegetation (adjacent to a waterway) intended to improve water quality by trapping contaminants from overland flow and shallow subsurface flow and by encouraging uptake of excess nutrients by vegetation.

Buffers are a popular BMP because they are inexpensive, relatively easy to implement because of the presumption they need little management after establishment and have been proven to be effective at reducing the transport of nutrients into surface waters. This has led to their widespread implementation across the globe, becoming mandatory through legislation in some areas (e.g., State of Minnesota 2016). In agricultural landscapes, buffers are designed to employ multiple mechanisms to protect surface water and improve water quality. These mechanisms include utilizing both the dense growth of vegetation above the surface and the extensive root systems of vegetation below the surface to trap sediments, reduce erosion, increase infiltration, increase uptake by plants and subsequently reduce P and other contaminant movement into surface waters. Several reviews have been published evaluating each of these aforementioned mechanisms (e.g., Hickey and Doran 2004; Dabney et al. 2006; Hoffmann et al. 2009; Zhang et al. 2010; Roberts et al. 2012). Additional reviews have determined buffer effectiveness based on one specific mechanism: the entrapment of sediments and particulate P (PP) from overland runoff (e.g., Liu et al. 2008; Yuan et al. 2009), P uptake by vegetation (e.g., Dorioz et al. 2006; Dosskey et al. 2010), and increased soil permeability through root channels (e.g., Dorioz et al. 2006). With specific regard to P, studies from temperate regions and some cold climates across the globe have shown that buffers can effectively filter soluble and particulate P, in some studies reducing loads by up to 90% (Barfield et al. 1998). Whereas buffer strips can decrease the quantity of water entering a stream as well as reduce erosion and the
transport of particulate P, water passing through bare fields or fields with a less dense vegetation cover do not do this and thus can increase bank and streambed erosion. Additionally, as runoff enters the adjacent waterway, there can be mobilization of particulate and soluble P that was previously stored in-stream (Svendsen and Kronvang 1993).

While buffers have proven to be an effective BMP in some climates, there are some concerns that over time they can become a source of P, particularly if they are left unmanaged. As noted by Kleinman et al. (2000), it has long been accepted that soil is a sink for P because of its ability to convert P to its stable phase through the adsorption process, but as P accumulates in the soil, the ability of soils to immobilize P begins to diminish. Consequently, over time as soils become more saturated, soil P can be mobilized through runoff events and become a source of P to the receiving water body. Buffers in cold climates generally behave differently with regards to the generation of surface runoff because runoff is more frequently driven by the snowmelt in the spring rather than precipitation events throughout the rest of the year (Jensen et al. 2001). There are exceptions to this generalization, such as the Chinook belt of southern Alberta, which experiences significantly less snowmelt runoff compared to the rest of the Canadian prairies (Maulé and Gray 1994). However, as described in Table 1, numerous studies throughout the Canadian prairies have shown that greater than 80% of annual runoff comes from snowmelt (Nicholaichuk 1967, Granger et al. 1984, Glozier et al. 2006, Little et al. 2007). This holds true not only in Canada, but in geographically diverse cold climates including the United States and northern Europe (Hansen et al. 2000; Syversen 2002), and snowmelt generated runoff can be the primary transport mechanism and period for P (Timmons and Holt 1977). Runoff generation and buffer processes during the snowmelt differ significantly from rainfall-induced runoff because of the impact of frozen soils and frozen vegetation. Frozen soils and/or vegetation reduce the ability
for soil erosion to occur, and also reduce the ability of snowmelt water to infiltrate into the soil column (Ginting et al. 1998). This process is important because it influences the type of P, soluble or particulate, being transported during surface runoff events (Table 1). Whereas in temperate climates where runoff is dominated by rainfall, and particulate P is the dominant form of P transported to surface waters, in cold climates dominated by snowmelt, soluble P is often the dominate form (Chanasyk and Woytowich 1987; McConkey et al. 1997; Jensen et al. 2011).

Another important environmental condition in determining VBS effectiveness is seasonality. Research by Schellinger and Clausen (1992) investigating VBS effectiveness in treating dairy barnyard runoff in Vermont, USA, found that there was a significant loss of total P (TP) and total dissolved P (TDP) during the snowmelt period, likely due to the inability for the VBS to retain water and nutrients when runoff rate increases during snowmelt (Schellinger and Clausen 1992). Furthermore, the decaying vegetation is covered by snow and ice throughout the winter and is not actively taking-up P (Sheppard et al. 2006, 2012; Lobb et al. 2012). In cold climates, the period of plant uptake of nutrients is shorter than in warm or temperate climates and, thus, P uptake occurs over a shorter period and does not include the peak runoff period, the spring snowmelt (Uusi-Kämppä 2005). Figure 1a illustrates how buffers are designed to effectively trap sediments and nutrients, increase infiltration and P adsorption, and encourage plant and microbial uptake and immobilization of P under temperate conditions. In contrast, Figure 1b illustrates the impact of conditions common in cold climates on reducing the ability for buffers to work effectively. Temperature is an important variable to consider because of the impact it will have on many of the processes that buffers are designed to encourage, particularly retention mechanisms such as biological activity and P sorption. Freezing temperatures can bring much of the biological activity in buffers to a halt, and Rajput et al. (2014) found that P sorption increases...
as soil temperature increases, which likely also means that P sorption declines with declining temperatures. Decreases in temperature can result in a reduction in the capacity of P fixation in soils, reduced microbial P cycling, and a reduction in the uptake of P by vegetation (Yli-Halla et al. 1995; Dorioz et al. 2006), all of which reduce the overall capacity for P retention in cold climates. Additionally, freezing can cause the concentration of soil solution into much smaller volumes, which can subsequently lead to the precipitation of P, particularly in soils containing high organic matter content (Ron Vaz et al. 1994; Peltovuori and Soinne 2005).

Other factors including microbial abundance, vegetation species diversity, VBS width, slope, and soil properties make it difficult to determine whether a buffer will act as a source or sink of P. For example, in a review of the effectiveness of buffers from across the globe, Hoffmann et al. (2009) found that reductions in dissolved reactive P (DRP) concentrations in runoff from VBS ranged from -71% to +95% and Gitau et al. (2005) found that filter strip effectiveness ranged from -56% to +59% for dissolved P (DP). These studies reinforce the idea that there are likely a number of physical and biogeochemical factors influencing buffer effectiveness given the difference in the climate, vegetation, and soil conditions in diverse agricultural landscapes.

While extensive reviews have been undertaken to determine the effectiveness of VBS (e.g. Norris 1993; Hickey and Doran 2004; Dabney et al. 2006; Liu et al. 2008; Hoffmann et al. 2009; Yuan et al. 2009; Dosskey et al. 2010; Roberts et al. 2012), there has not been a review of the literature that pertains solely to VBS in landscapes in cold climates, defined here to include long periods of temperatures below 0 °C and precipitation dominated by snow during these periods. Thus, the primary objective of this review is to collate much of the research undertaken investigating the effectiveness of VBS in reducing P delivery to surface waters in cold climates, with a focus on North America and northern Europe. There is a focus on these regions because
this is where nearly all cold climate VBS research has been undertaken, but the two regions
remain separate in this review due to the important differences in their climate and physical
properties, further detailed in section 3.3. A secondary objective is to summarize the research of
the potential for P release from vegetation and soils that have undergone winter conditions (i.e.
prolonged temperatures at or below 0 °C and/or multiple freeze-thaw cycles (FTCs) followed by
runoff. The final objective is to identify gaps in the research of VBS in cold climates that need to
be addressed to understand how VBS perform in these conditions and ultimately lead to
improved design and management of buffers in cold climates.

2 Research approach

Research papers were sourced using various search engines including, but not limited to,
Google Scholar, Science Direct, and Wiley Online Library. Searches were also undertaken in
specific journals and included the search terms: buffer strips OR vegetated buffer strips OR filter
strips AND cold climate OR northern climate, AND nutrients OR phosphorus. The determination
of what was considered a cold climate landscape was based on a modified and updated version of
the Köppen-Geiger climate classification (Peel et al. 2007). The study locations of papers
included in this review were all classified in group D: cold climates (Figures 2 and 3). Each of
the studies included in the review were in locations where it was determined there was no dry
season (subclass f), but they were further classified as hot summer (subclass a) or warm summer
(subclass b) cold climates. Explanations of the thresholds that determine subclasses can be found
in detail in Peel et al. (2007). Buffer effectiveness studies where sites were not located in the
cold climate zones were not included in the review.

Results are presented in this paper as they were presented in the original journal article,
which is important to note as different studies inevitably report different metrics including:
concentrations; loads; and flow-weighted mean concentration (FWMC). Each of these metrics are of interest but are used differently. The reporting of concentrations is more useful for comparing to water quality guidelines, whereas loads are more useful in determining the effectiveness of the treatment (Magette 2001). When comparing watersheds or streams that may have similar loads but different streamflow, FWMC is the best measure because it includes both load and streamflow (Sether et al. 2004).

3 Effectiveness of buffers in reducing phosphorus

3.1 North America

Much of the research investigating VBS as a nutrient reduction management practice in cold climates in North America has been focused in the Lake Winnipeg Basin (Table 2, Figure 2), in part due to the occurrence of annual algae blooms in Lake Winnipeg that are the product of excess P making its way into tributaries and ultimately into the lake. In research to determine if VBS were effective in reducing P concentrations in runoff, Sheppard et al. (2006) selected 14 sites within five regions in southeastern Manitoba, Canada, and sampled VBS runoff and soils. The VBS primarily were composed of natural vegetation or a mix of grass and sedge with minimal management, and soils varied from clay loam to sandy loam. The soil samples were collected in the flow path of the VBS, in the adjacent cropped field, and at the field edge, and runoff samples were collected at the field edge and within the flowpath in the VBS. For analysis, runoff samples were paired, with pairs considered the edge of field and within the VBS. The authors found that half of the 22 paired sampling instances reduced TDP and TP concentrations, while seven of the 22 instances showed no significant difference. However, samples from four of the 22 paired sampling cases resulted in increased TDP and TP concentrations. Additionally, soil samples from within the flow path showed that in seven of 10 sample locations, the buffer soils
were higher in P than the adjacent fields (Sheppard et al. 2006). The results of this study indicate
that the effectiveness of buffers is varied and that in some instances they can become a source of
P for receiving waterways.

Habibiandehkordi et al. (2017) combined their analysis with that of Sheppard et al. (2006)
and found that their results were comparable, pointing to the inability for most of the
mechanisms that buffers are designed for (see Figure 1a) to function during the spring snowmelt
period (see Figure 1b) as the reason for the overall ineffectiveness of buffers in these landscapes
(Sheppard et al. 2006; Habibiandehkordi et al. 2017). Undertaken across three sites within the
Lake Winnipeg Basin in Manitoba, Habibiandehkordi et al. (2017) monitored runoff through
buffer strips from 2009-2011 and found that there were no significant trends in the reduction of
TP, DP, or PP in surface runoff samples taken 0.5 m and 5.0 m into a VBS. Statistical ranking
analysis was undertaken due to the non-normality of the data, and did show that at one of the
three sites, TP concentrations in snowmelt runoff samples were significantly reduced in each of
the three years of monitoring and that PP concentrations at this site were also reduced over three
years during summer and fall, but not during spring. Thus, it is reasonable to conclude that the
VBS was effective as a filter for sediment and PP, reducing concentrations of TP. However, DP
was significantly reduced in only two of 17 sampling events and only at a single site.

Additionally, VBS significantly reduced concentrations of TP, PP, and DP in just 23%, 12%, and
12% of all sampling events, respectively (Habibiandehkordi et al. 2017). These results vary
considerably from the results of studies undertaken both in controlled environments and under
natural conditions that induce runoff through artificial rainfall, and which often tend to show a
more consistent pattern and magnitude of P retention in VBS (Sheppard et al. 2006).
In an investigation of the differences in P flux during snowmelt and growing season in the Bow River watershed in southern Alberta, Canada, a tributary to the South Saskatchewan River, Ontkean et al. (2005) compared P release from annual crops and grasslands. There were significant differences in the type of P released from sites under the different vegetation types. In the site comprised of ~40% grassland, a significant portion of which was adjacent to the stream and thus acted as a buffer, 31-97% percent of TP was released as TDP during runoff events in spring whereas at the site comprised mostly of annual crops and without grass adjacent to the stream, just under 50% of TP was released as TDP during the May runoff event. While the grasslands in this study were not buffers, this work parallels the research on P release from buffer vegetation because grassland species can be planted in or naturally occur in many VBS. Much of the research in warmer or more temperate climates has shown buffers to be most effective in reducing particulate P transport, but this study provides further evidence that P loss in runoff in cold climates is dominated by soluble P (Ontkean et al. 2005; Stutter et al. 2009; Uusi-Kämppä and Jauhiainen 2010). Within the drainage area of the two sites in the Bow River watershed, slope gradients varied from 2-16% and the authors suggest that the steep areas discouraged infiltration of snowmelt and rainfall (Ontkean et al. 2005). These results emphasize that while vegetation is an important physical characteristic to be considered when determining buffer effectiveness, so is the slope of the buffer. In a meta-analysis of factors impacting buffer effectiveness on sediment trapping, Liu et al. (2008) found slope and buffer width to be the most important factors determining the buffer’s capacity to trap sediments and nutrients.

Research on VBS in cold climates in North America has been primarily undertaken in the Canadian prairies, but much of the northern United States, including Minnesota, Wisconsin, Iowa and Ohio contain large areas of agricultural land that experience winters where soils and
vegetation undergo long periods of freezing and numerous FTCs. While there has not been a substantial amount of research explicitly investigating the effectiveness of VBS in these areas, a wide range of field and modeling projects have been undertaken with varying results.

Lake Erie (which lies on the Canada/USA border), much like Lake Winnipeg, has been a target of non-point source P reduction strategies due to toxic algae blooms that as recently as August 2014 forced the city of Toledo, Ohio, USA (Köppen climate classification Dfa: humid continental climate with at least one month <0 °C), to declare a State of Emergency and issue a tap water ban, which left 500,000 people without drinking water (Kilpatrick 2014). Much of the land use in the watershed is agricultural, including the Maumee River basin which has been identified as one of the greatest contributors of non-point source P (Robertson and Saad 2011).

Research on the potential P losses from monitored fields containing different BMPs including grassed waterways was undertaken by researchers from the U.S. Department of Agriculture (USDA) in the Saint Joseph River watershed, a tributary to the Maumee River located in northern Indiana and Ohio, USA (Smith et al. 2015). While grassed waterways are not always designed to filter nutrients in the same way as VBS and, in this study, the location of the grassed waterway was not directly adjacent to a stream, this study is relevant because its purpose was to determine the effectiveness of the grassed waterways in reducing P concentrations in runoff in much the same way VBS are designed to do. When analyzing soluble P and TP losses from the grassed waterway, the authors found that there was a significant increase in surface runoff FWMC of soluble P from 0.08 mg L$^{-1}$ before implementation to 0.21 mg L$^{-1}$ after implementation. When looking only at the growing season, the difference was even greater with surface runoff soluble P loads increasing from 14 g ha$^{-1}$ before the waterway was planted to 81 g ha$^{-1}$ after (Smith et al. 2015). The authors conjecture this dramatic increase in load could be
caused by the enrichment of surface soil particles in P that is then remobilized during subsequent
runoff events, or by the inability for the grassed waterway to efficiently trap P when runoff
occurs as concentrated flow rather than uniform sheet flow (Smith et al. 2015). Sediments stored
in the grassed waterway as well as its vegetation could have been a source for soluble P release,
particularly due to the ‘age’ of the grassed waterways. They were implemented in 2006 and
2010, and the duration of the study was 2004-2013 and, thus, their effectiveness over time could
have been diminished.

In a similar study in Nebraska, USA (Köppen climate classification Dfa: humid continental
climate with at least one month with temperatures <0 °C), Al-wadaey et al. (2012) compared
concentrations of TP, DP, and PP in surface runoff from cultivated fields that contained 0%,
1.1%, or 4.3% VBS area within a cultivated field. The authors point out that even in Nebraska,
which does not experience the prolonged periods of snow cover and freezing temperatures that
are typical of the northern USA or Canada, soils are still frozen and vegetation is not actively
taking-up nutrients over winter (Al-wadaey et al. 2012). Thus, runoff with limited infiltration is
likely occurring, which has been shown to increase DP loads to surface waters. Vegetation in the
VBS was a 70:30 mixture of tall fescue and orchard grass that was transplanted to ensure
adequate cover for the runoff experiments. During the single snow event, concentrations of TP,
DP, and PP were higher in both the 1.1% and 4.3% VBS plots compared to the cultivated field
containing 0% VBS with the 1.1% plot containing the highest concentrations of TP (4.8 mg L⁻¹)
and DP (4.29 mg L⁻¹) of any sample during the study (Al-wadaey et al. 2012).

The vegetative species established in buffers varies greatly based on location and climate
and, thus, the potential for release of P from these species has been the subject of a number of
studies (e.g., Miller et al. 1994; Lee et al. 2003; Elliott 2013; Øgaard 2015). Little et al. (2007)
monitored P loss from cultivated croplands and native prairie in micro-watersheds across Alberta, Canada. They found that concentrations of TP in runoff from the native prairie were similar to concentrations of TP from the cultivated fields even with soil P levels that were significantly lower. The authors attribute the similar concentrations of TP despite lower soil P to the potential release of P from the vegetation in the native prairie that was not present in the cultivated fields (Little et al. 2007). These results have subsequently been corroborated by research detailed in section 3.4 (Liu et al. 2014), and while this study was not explicitly investigating VBS, important conclusions can be gleaned from it with regards to what species of vegetation to plant in VBS.

In summary, much of the work undertaken in North America has confirmed that VBS in cold climates may not be as effective as those in more temperate climates. Results from Smith et al. (2015) in Ohio, and Al-wadaey et al. (2012) in Nebraska found that the implementation of a grassed waterway and VBS, respectively, increased concentrations of DP and TP compared to cultivated fields. Results from the two studies in Manitoba similarly found that VBS were only effective sometimes, reducing TP in just 50% of runoff scenarios (Sheppard et al. 2006) or 23% of runoff scenarios (Habibiandehkordi et al. 2017). While results from Little et al. (2007) and Ontkean et al. (2005) did not determine the overall effectiveness of VBS, they did find that vegetation and soils can become a source of P.

### 3.2 Northern Europe

A significant amount of research has been undertaken in northern Europe on the effectiveness of buffers as BMPs, particularly from Norway, Sweden and Finland (Table 2). The climate in these Nordic countries is more temperate than the North American prairies, as they experience warmer minimum winter temperatures and mid-winter melts, but each of the study
site locations (Figure 3) are still considered to be cold climate landscapes (Dfc or Dfd) according to the Köppen climate characterization (Peel et al. 2007). The coldest months maintain an average temperature below -3°C and runoff primarily occurs during winter snowmelt periods (Ahlstrøm and Bergman 1990; Lundekvam and Skoien 1998; Syversen 2005).

In a review of studies of VBS efficiency from Norway, Sweden and Finland, Uusi-Kämppä et al. (2000) compiled data from nine VBS studies and found that in all but one VBS were effective in retaining P. The single study suggesting that the buffer was a source of P was from Sweden, where buffer efficiency, calculated by comparing runoff P from a control strip to runoff P from a vegetated buffer, was -36% (Ulén, 1988). In Norway, buffers of varying widths were found to retain 0.5 g m\(^{-2}\) to 4.4 g m\(^{-2}\) of P (Syversen, 1997) whereas in Finland, buffers of varying species were found to retain 2.7 g m\(^{-2}\) to 3.8 g m\(^{-2}\) of P (Uusi-Kämppä and Yläranta 1992, 1996).

Numerous studies across these Nordic countries have been completed since the Uusi-Kämppä et al. (2000) review to determine if factors such as vegetation species, buffer width, seasonal variation or management strategies impact VBS effectiveness. In research undertaken in southern Norway by Syversen et al. (2001), VBS that differed in width and vegetation type were used to determine buffer efficiencies for removing P after the VBS underwent both simulated and natural runoff events. Results from this study showed that the removal efficiency of P was greater in 10-m wide VBS, but the specific efficiency per unit total buffer area, measured in m\(^2\), was greater in 5-m wide buffers because the upper portion of the buffer is where most deposition occurs (Syversen et al. 2001). There was no significant difference between summer and winter runoff events, but VBS in summer retained 4.6% more P than autumn events, likely due to the greater trapping efficiency of sediment-bound P, and potential uptake and adsorption of P in the...
summer months (Syversen 2005). When comparing VBS of different vegetation, the authors found that there was no significant difference in retention of P in a forested buffer, consisting of aspen and mosses, compared to a grass buffer (Syversen 2005). Another study with the explicit objective of determining the effectiveness of VBS in cold Nordic climates undertaken in Norway found that in 5 m and 10 m wide buffers, P removal efficiency was 76% and 89%, respectively, when comparing runoff samples upslope from the VBS and at the downslope outlet of the VBS (Syversen 2002). This study found that the retention of P in VBS during the winter was 15-35 times greater than in the summer, though this difference was not statistically significant. Additionally, while the author found that 90% of runoff occurs during the winter months, this is not necessarily primarily during the spring snowmelt, but instead during multiple runoff events that happen throughout winter, defined as December through March (Syversen 2002).

To address the question of VBS effectiveness specifically during the snowmelt period, Väänänen et al. (2006) added 60 kg ha\(^{-1}\) of PO\(_4\)-P as well as 1100 MBq ha\(^{-1}\) of radioactive \(^{32}\)P to runoff water in Finland and measured its retention in a VBS that ranged from 25 m to 50 m in width. They found that just 16% of added \(^{32}\)P was retained within the buffer, of which 92% was retained in the soil. Mosses and vascular plants in the buffer retained just 5% and 3% respectively, likely because of the inability for runoff water to infiltrate deeply enough to be used by vegetation. The authors note that the lack of infiltration was likely due to the inability for runoff to be sufficiently slowed down due to minimal contact with vegetation and soil because the hydraulic load was significantly greater than it would be under than normal, non-experimental conditions. The major sink for P in this study was adsorption by surface soil which is not ideal for long term P storage (Väänänen et al. 2006).
While VBS have been proven to be effective in reducing P transport in some studies in Nordic countries (e.g. Uusi-Kämppä and Yläranta 1992, 1996; Syversen 1997), other studies have shown that, as was evident in work throughout North America, the vegetation within the buffer can potentially be a source of P. In an experimental plot study by Uusi-Kämppä (2005) in southwestern Finland, the retention of PP and loss of DRP in runoff samples were compared between three treatments: i) grass buffers planted with timothy (*Phleum pratense*) and meadow fescue (*Festuca pratensis*) that were mowed; ii) natural vegetation buffers populated with scrub plants, hardwood trees, wild hay and flowers, that were unmanaged; and iii) no buffers. Results showed that buffers were effective in retaining PP, but loss of DRP was significant, particularly in the natural vegetation buffers, where losses were 70% greater than the grass buffer or the field with no buffer (Uusi-Kämppä 2005). Additionally, samples from the spring snowmelt showed that DRP losses in the natural vegetation buffers increased by 110% whereas DRP losses from the grass buffer and the field with no buffer did not change. Finally, in the one year when the grass buffer was not mowed, DRP concentrations were nearly as high (0.18 mg L$^{-1}$) as the unmanaged, natural vegetation buffers (0.19 mg L$^{-1}$). The authors conclude that the increase in DP from buffers is likely a product of release from decaying vegetation in the buffers.

Thus, results from studies undertaken in the Nordic countries were varied in their determination of the effectiveness of VBS. Just two studies, Ulén (1988) and Uusi-Kämppä (2005), were comparable to the North American research that found that buffers were potentially a source of dissolved P. However, Uusi- Kämppä (2005) found that the VBS planted to native vegetation was still very effective at retaining PP, and studies by Syversen (1997, 2001, 2002, and 2005) and Uusi- Kämppä and Yläranta (1992, 1996) found that buffers were very efficient at retaining P, with some retention rates as high as 89%. Unlike in North America where specific
sites varied but generally showed similar trends, there are significant differences across studies within northern Europe, and many of these findings are a significant departure from the findings in cold climates in North America.

3.3 Regional differences

The reason for the substantial differences in the results from North American and northern Europe is likely due to two main factors: i) climate; and ii) slope of buffer. While the Nordic countries are considered cold climates, they do not always experience the prolonged freezing temperatures over the entire duration of winter that is typical of the North American prairies. In northern Europe, intense precipitation events occur during the winter, but numerous snowmelt and runoff events also occur at multiple points throughout the winter season (Ulén 2005).

Additionally, sub-zero temperatures in Nordic landscapes may not be reached until well after plowing, and, combined with heavy autumn rains, can cause significant runoff of nutrients before the spring melt period (Uusi-Kämppä 2005).

The second difference between landscapes of the Nordic countries and the North American prairies is slope gradient. While the prairies are primarily flat, many of the studies undertaken in the Nordic countries occur in steeper landscapes with slope gradients as steep as 20%, which can encourage soil erosion and sediment transport (Syversen 2002). In a review of buffer effectiveness, Liu et al. (2008) used a polynomial regression of data collected from across the US, Canada, and Europe and determined that as buffer slope increases, so too does buffer efficacy until a 9.2% slope is reached, at which point buffers become less effective. The 9.2% threshold as a maximum is likely due to both the steeper slopes creating runoff at velocities that are too great for the buffer to be an effective trap, and for the tendency for flow to concentrate at steeper gradients. At minimum, the authors note that a 9% slope is ideal because below that
threshold there is insufficient hydraulic gradient to create a flowpath to the buffer (Liu et al. 2008).

It is for these reasons that it is not advisable to draw strong conclusions about the effectiveness of VBS across the two regions, but instead to keep them separate, even as they share a specific climate designation. While the results from research in North America are clearer in concluding that VBS are rarely effective at trapping P and often become a source of P in the spring, results from northern Europe are far more varied and broad conclusions cannot be made.

3.4 Phosphorus release from vegetation after controlled and natural runoff events

Buffers can become a source of P due to release from vegetation and residue during runoff events (Timmons et al. 1970; Miller et al. 1994; Bechmann et al. 2005). While there has been a limited amount of work on this issue specifically in VBS in cold climates, there is a reasonable body of work investigating P release from various species of vegetation in agricultural systems in cold climates. This work is relevant to buffers because in locations where planting specific species of native vegetation is not mandatory, forage crops such as timothy or alfalfa can be planted in buffers.

In research undertaken in southeastern Saskatchewan, Canada, a comparison of runoff from annual cropland and pasture found that while there was no difference in TP concentrations between crop and pasture, the FWMC of DRP was significantly greater in runoff from annual cropland (wheat – canola rotation) than from perennial tame pasture (brome – alfalfa mix), whereas PP was significantly greater in pasture than cropland. Additionally, DRP comprised 97% and 100% of TDP from pasture and cropland respectively (Cade-Menun et al. 2013). In a similar study, Liu et al. (2014) compared the FWMC and load of TDP and TP in runoff collected
from fields planted to annual crop and to perennial forage over 8 years in a watershed in Manitoba, Canada. Their results showed that, compared to the annual crop treatment, perennial forage increased the FWMC of TDP and TP by 53% and 52%, respectively, and increased the load of TDP and TP by 221% and 160%, respectively (Liu et al. 2014).

Additionally, in a four-year study in southern Norway, biomass from three species: Italian ryegrass (*Lolium multiflorum*), white clover (*Trifolium repens*), and meadow fescue (*Festuca pratensis*), was harvested in fall and spring and analyzed for TP to determine potential P loss over winter (Sturite et al. 2007). Results showed that losses in P from aboveground biomass ranged from 11-60% over the winter period. This study also analyzed seepage water for TP and found that of the 11-60% of biomass P lost, only 34% (+/-9%) was recovered in the seepage water. However, the authors note that some of the potential loss from vegetation was likely used by soil microbes and thus was not completely lost to runoff (Sturite et al. 2007).

Release of P from numerous species of vegetation and of crop residue or stubble has been widely studied both in the laboratory and in the field. Øgaard (2015) completed a comparative study of the P release capacity of eight different plant species under natural growing conditions in Norway. Samples of each species were taken in spring and again in fall and subjected to a water extraction to determine P loss over two consecutive winters. Results showed that 18-48% of biomass TP was released, but species varied between the two years of the study. Combining the data from both years, results showed that timothy grass (*Phleum pratense*) released greater concentrations of P than smooth meadow grass (*Poa pratensis*) or meadow fescue (*Festuca pratensis*). Additionally, 55-91% of extractable TP was released as DRP, an important finding because DRP is a more bioavailable form of P. In a similar study undertaken near Saskatoon, Saskatchewan, Canada, 11 different types of residues underwent a snowmelt runoff simulation
where runoff was captured and analyzed for TDP and TP (Elliott 2013). The results of this study found the greatest release of TDP (3.57 kg ha\(^{-1}\)) and TP (3.71 kg ha\(^{-1}\)) from newly planted clover forage, followed by winter wheat that was actively growing at the time of collection (1.46 and 1.47 kg ha\(^{-1}\) respectively) and riparian grasses (0.87 and 0.89 kg ha\(^{-1}\) respectively). The five species of crop stubble released significantly lower TDP (0.00-0.13 kg ha\(^{-1}\)) and TP (0.02-0.23 kg ha\(^{-1}\)) than any of the other vegetation. Both of these studies show that in cold climates where spring snowmelt is the dominant form of runoff, vegetative residues from numerous species that potentially could be planted in buffers can release P and, thus, the type of species planted in buffers can significantly influence potential P loss to waterways.

After their implementation, buffers must be managed strategically because of the tendency for unmanaged vegetation to become a source of P. The objective of a study in southwestern Finland was to determine the differences in biomass P and biomass WEP at different times throughout the year in both old (14 years) and young (3 years) VBS that were composed of different species and managed differently (Räty et al. 2010). Treatments included: (i) an unmanaged VBS composed of native wild species; (ii) a VBS primarily composed of timothy and meadow fescue where vegetation was harvested and removed; and (iii) a VBS composed of timothy and meadow fescue that was grazed. Undertaken in natural conditions, the buffer vegetation was sampled continuously from May 2005 to November 2005 and again in April 2006, ensuring that samples were taken to reflect changing seasons and capture P loss temporally. The young, grazed VBS performed best, losing only 0.5 kg ha\(^{-1}\) of P compared to the old, unmanaged native species VBS which lost 6.1 kg ha\(^{-1}\) of P. Across all treatments, loss of molybdate reactive P – a measure of DRP – constituted 61-100% of TP loss, though the extraction procedure of drying and grinding the vegetation and shaking it for 18 hours may have
overestimated loss (Räty et al. 2010). Additionally, the authors found that there was a significant decrease in biomass TP between vegetation sampled in October and November; before and after the first frost. They note that this is likely due to the translocation of P from shoots to roots which was noticeable in P concentrations of root samples (Räty et al., 2010). It is also important to note that these concentrations are only a measure of the loss of DRP contained within the biomass, and this study did not include a measure of PP loss. The authors state that because buffers are designed to reduce erosion and trap sediment-bound P, these buffers still could reduce P transport to surface waters, but that management and age of buffer are important variables to consider.

As research shows buffers as a potential source of P in cold climates, strategic buffer management has become a research focus. To determine the potential impact of harvesting buffer vegetation as a management strategy (detailed further in section 6), Roberson et al. (2007) investigated the potential release of P from buffer vegetation in Wisconsin, USA, under various harvesting treatments. Alfalfa was either untreated (i.e., full growth stage) or removed by cutting (i.e., harvested) whereas mixed grasses including quackgrass (Agropyron repens), smooth brome grass (Bromus inermis) and orchardgrass (Dactylis glomerata) were left unharvested or were treated with paraquat, an herbicide treatment that simulates freezing. All vegetation treatments were subjected to both natural runoff conditions and runoff derived from simulated rainfall and comparisons were undertaken to determine the potential for buffer vegetation to become a source of P. The authors found that in the simulated rainfall experiments the removal of alfalfa significantly increased concentrations of TP in buffer runoff compared to alfalfa that had not been harvested, likely due to the increased volume of runoff from bare soils and thus, the removal of more sediment. However, while there was no difference in TP concentrations in the
runoff samples between the harvested alfalfa and the paraquat treated mixed grass, the paraquat treated mixed grass released greater concentrations of DP (0.52 g L\(^{-1}\)) than the alfalfa (0.03 g L\(^{-1}\)).

In summary, significant research has been done to understand better the potential for P release from vegetation, and each of the above described studies found that vegetation can be a readily available source of P, and of dissolved P in particular. However, it is much more difficult to make broad conclusions about specific species and management techniques. Results from Cade-Menum et al. (2013) found that annuals release significantly greater FWMC of DRP, whereas Liu et al. (2014) found that perennials released significantly greater FWMC of DRP. In agreement with Liu et al. (2014), Elliott (2013) found that crop stubble released lower concentrations of TDP and TP than all other vegetation including perennials. Comparing the research that aimed to determine best management strategies is more difficult as there was little overlap of treatments, though Sturite et al. (2007) and Øgaard (2015) both found significant loss of P over winter (11-60%). Thus, before it is possible to make strong recommendations for vegetation species and management in cold climate VBS, significantly more research is needed, and is outlined in section 5.

3.5 Phosphorus release from vegetation and residues undergoing numerous freeze-thaw cycles (FTCs)

The vegetation in a buffer at the time of snowmelt will behave differently than vegetation in rainfall-induced events later in the season when the vegetation is actively growing. During the snowmelt period, vegetation can become a source of soluble P as senesced vegetation can release P during runoff events (Turtola and Jaakkola 1995; Hickey and Doran 2004). As noted by Roberts et al. (2012), during leaf senescence, P-solubilizing exudates can be responsible for the
conversion of particulate P (PP) to soluble P (SP) forms. In cold climates, vegetation often undergoes multiple freeze–thaw cycles (FTCs) in the fall and spring, which increases the amount of P available for release during spring runoff. As vegetation freezes, the cells in the shoots can lyse due to ice crystal formation and, when this occurs, cells will pull water from adjacent cells (Levitt 1980; Webb et al. 1994). This damage and subsequent movement of water between cells will lead to inter/intra-cellular P release from the biomass that can release P into runoff and carry it to nearby streams and rivers, which is especially apparent during the spring snowmelt, when snow runoff carries soluble P (Jensen et al. 2011).

An increasing amount of research has been undertaken to understand the potential for release of soluble P from a variety of species of crops, native vegetation, and forage grasses after various FTCs and extraction methods (Table 3). Though some studies relied solely on simulated or natural runoff events, the studies described below and in Table 3 primarily used shaking as the extraction method, and all used water as the extractant. Results from a study in the South Tobacco Creek watershed in southern Manitoba, Canada, in which field residue of perennial forage and annual crops that had undergone freeze-thaw conditions and water extraction, found that annual crop residue released significantly less P than perennial grass residue (Liu et al. 2014). Additional research within this watershed found a similar trend where perennial forage release of P averaged 5.9 and 3.1 kg ha$^{-1}$ in October 2005 and 2006, respectively, compared to annual crop which released just 0.2 and 0.1 kg ha$^{-1}$ on replicate samples taken in October 2005 and 2006, respectively (Saleh 2008).

Buffers are planted to a variety of different species depending on whether they are part of a specific conservation program or are voluntarily implemented by a landowner, and each of these species have different P release potential. In a study on field-grown vegetation in southwestern
Ontario, Canada, Miller et al. (1994) used simulated rainfall to determine the P release potential from ryegrass (*Lolium multiflorum*), red clover (*Trifolium pratense*), and oilseed radish (*Raphanus sativus*) that had undergone either one FTC (-18°C to +30°C) or just a freeze (-18°C). For extractions, the samples that were only frozen were first thawed, then underwent a rainfall simulation, followed by a re-freeze and second rainfall simulation. The samples that underwent one FTC were also subjected to a rainfall simulation followed by re-freezing, thawing and second extraction. Results showed that samples that underwent one FTC released significantly more P than samples that were only frozen in the first extraction, but not in the second. Additionally, 20-33% of biomass P was released during the extractions and depending on species, 1-16 mg L\(^{-1}\) P was released during a runoff simulation event, with the lowest concentrations (1-3 mg L\(^{-1}\)) coming from red clover (Miller et al. 1994).

In addition to the differences in P release potential from different species, vegetation undergoing varying numbers of FTCs will also differ in their release potential. In the aforementioned Roberson et al. (2007) study in Wisconsin, USA (section 3.4), laboratory experiments were undertaken to determine the potential for release of P from alfalfa and mixed grasses undergoing various treatments: fresh, frozen, frozen and thawed, and dried. Results showed that both the alfalfa and mixed grasses released significantly higher concentrations of TDP and DRP after the freezing, freezing/thawing, and drying treatments than from fresh vegetation. For nearly all of the species, dried vegetation released the highest concentrations of DRP and TDP followed by frozen and frozen/thawed (Roberson et al. 2007). The authors note that P loss from vegetation is dependent on other environmental conditions such as timing of freezing and precipitation events as well as laboratory variables such as the duration and magnitude of freezing and drying vegetation (Roberson et al. 2007). Analyzing results from both
the runoff experiments (section 3.4) and these FTC experiments, the authors suggest that using harvesting as a management strategy has the potential to reduce P release from vegetation, but could potentially lead to release of P from soils.

In another study on the potential impact of freezing and thawing on vegetation and soils, Bechmann et al. (2005) completed a laboratory experiment with the objective of determining P loss in surface and subsurface flow after subjecting soils and vegetation to multiple FTCs. In incubation experiments, soils and biomass were subjected to none, one, two, six or eight FTCs followed by a water extraction and analysis of biomass TP. Results showed that in fresh biomass (i.e. 0 FTCs), just 0.9% of TP was released as water extractable P (WEP). However, in biomass undergoing freezing and thawing, WEP was more than 40% of TP and, as the number of FTCs increased, WEP concentrations increased logarithmically. After eight FTCs, all of the biomass TP was released as WEP (Bechmann et al. 2005). While these values are significantly greater than previous research (e.g., Miller et al. 1994), likely due to the greenhouse grown vegetation which would not have been adapted to the cold climate, the results still highlight the ability for P to be released from vegetation.

In one of the earliest published studies on the ability for P to be released from frozen and thawed vegetation, Timmons et al. (1970) subjected numerous species to varied freeze-thaw regimes (Table 3), followed by soaking and percolation of water through the vegetation sample. Results showed that in alfalfa, 77-87% of TDP was released as DRP and 31-53% of biomass TP was released as TDP (Timmons et al. 1970). These results correspond well with those of Bechmann et al. (2005) who found that after eight FTCs, 100% of biomass TP was released. However, these results are different from other FTC experiments undertaken in Norway comparing the potential release of P from various species. Øgaard (2015) compared eight species
for their P release potential after they underwent multiple FTCs. The vegetation was subject to zero to seven FTCs and results showed that, similar to the field studies, 67-82% of extractable TP was released as DRP. After seven FTCs, oilseed radish released 32% of its total biomass P whereas the other seven species released less than 15% of their biomass TP.

As Table 3 indicates, there has been a significant amount of research to determine the potential for P to be released from vegetation. However, research to determine the potential of P to be released from soils has been less common but is of importance, particularly under scenarios where buffer vegetation is harvested and removed from the landscape. Bechmann et al. (2005) investigated the potential for P release from soils undergoing multiple FTCs through runoff and leaching experiments. The results of the runoff experiments showed that concentrations of DRP in runoff from frozen soils containing catch-crop vegetation were increased 100 times compared to unfrozen soils, whereas TP losses were increased 37 times. However, when soils were unfrozen, even if vegetation was frozen, there was no increase in the concentrations of P in leachate (Bechmann et al. 2005).

The focus of most of the research on potential P release from buffer vegetation is on the shoots of biomass, but roots have also been considered. A laboratory study undertaken in Sweden by Liu et al. (2013) was designed to determine differences in P release in the roots of multiple species including perennial ryegrass (*Lolium perenne*), cocksfoot (*Dactylis glomerate*), chicory (*Cichorium intybus*), phacelia (*Phacelia tanacetifolia*), red clover (*Trifolium pratense* L.), white mustard (*Sinapis alba*), oilseed radish (*Raphanus sativus*) and white radish (*Raphanus sativus* var. *longipinnatus*). Liu et al. (2013) subjected roots of these annual and perennial species to four different freeze-thaw regimens: zero, one, or four FTCs. For nearly all species, root samples that underwent zero FTCs released the least WEP, but there was no difference
between roots undergoing one or four FTCs, and up to 96% of TP was released as WEP. The authors concluded that while roots can be a source of P after undergoing FTCs, they are likely not the main contributor of P lost from buffer or cover crop vegetation (Liu et al. 2013). This study also examined P release from shoot biomass and found that P release from annuals was greater than perennials across all FTC treatments and, in agreement with Bechmann et al. (2005) and Øgaard (2015), that concentrations of WEP increase with increasing FTCs.

The results from these studies aimed to determine the extent of the ability for vegetation to release P after undergoing numerous FTCs. While there were important differences in the results, it is clear that both perennial and annual biomass that is often planted in buffers can become a source of P. However, while some studies found that perennials released greater P than annuals (Saleh 2008; Liu et al. 2014), other studies found the opposite (Liu et al. 2013). Additionally, while each of the studies found that as the number of FTCs increased the concentrations of WEP also increased, there was a wide range as to the percent of biomass TP released as WEP (15-100%). This is likely due the differences in species, growing conditions, FTC temperatures and timing, and extraction protocols.

4 Models used to investigate buffer effectiveness in cold climates

While field-based research is important because of its ability to capture the natural processes occurring within the studied region, it can be expensive, time consuming, and difficult to relate to the catchment scale. Water quality models can be problematic because of the necessary assumptions made, but various models specific to agricultural landscapes have been developed and widely used to understand the impact of buffers of different widths, slopes and vegetation composition on a much larger scale and under varying climatic conditions. Additionally, in order
to deal with cold climate conditions, hydrological models have been developed to better predict spring runoff.

The Vegetated Filter Strip Modeling System (VFSMOD) is a field-scale model designed to predict values of infiltration, outflow, and sediment and P trapping efficiencies of VBS during individual precipitation events. It uses length, slope, width, vegetation type and numerous other input parameters in concert with measures of infiltration and storm pattern and intensity to ultimately determine optimal parameters in the design of buffers (Muñoz-Carpena et al. 1993). Its accuracy in predicting sediment trapping efficiency has been validated in the southern USA (Muñoz-Carpena et al. 1999), but there have not been substantial validation studies undertaken to specifically address the issues associated with cold climates, where infiltration and storm intensity would vary significantly during the spring melt period. Abu-Zreig et al. (2001) validated the model in Ontario, Canada, but focused only on runoff from simulated rainfall events and did not test it under snowmelt conditions. Li and Simonovic (2002) developed a dynamic model intended to predict runoff in order to address better the generation of floods due to snowmelt associated processes. The model was successful at predicting discharge on the Assiniboine and Red Rivers in northern Minnesota, USA, and southern Manitoba, Canada, with $R^2$ values of 0.92-0.96 and 0.89-0.97, respectively, but it did not directly address the effectiveness of buffers or predict P concentrations in runoff. However, its ability to accurately assess the impact of frozen soils and vegetation could be a useful addition to other models and in fact forms the basis for the algorithms used in another widely used model; the Soil and Water Assessment Tool.

The Soil and Water Assessment Tool (SWAT) is a widely-used river basin-scale modeling tool that employs a range of landscape and climatic inputs to quantify the effect of varying land
management and land use practices on nutrient and sediment loads (Arnold et al. 1993). The
SWAT model includes seven snowmelt related parameters, but these parameters are limited to
the extent of the snowpack and the timing and intensity of spring runoff, and do not include
parameters relating to winter and spring soil conditions. Starkloff et al. (2017) state that soil
water content at freezing and tillage practices prior to freezing among other variables are
important when evaluating buffers in cold climates where runoff occurs primarily in the spring.
As such, SWAT has proven to be limited in its suitability for cold climate landscapes because of
its inability to adequately assess runoff over frozen ground, infiltration into partially frozen soil,
and freeze-thaw dynamics in soils and vegetation (Mekonnen et al. 2016). However, in an effort
to mitigate this issue, work undertaken by Mekonnen et al. (2017) added probability distributed
landscape depressions (PDLD) that allow the model to, among other things, take seasonal
variation of sediment and nutrient movement into account through an erodibility index.
According to the SWAT-PDLD model for the Assiniboine and Moose Jaw River watersheds in
Saskatchewan, Canada, buffers ranging in width from 1-30 m could reduce TP loading by 15.7-
59.7% annually (Mekonnen et al. 2017). However, TP reduction based on sediment reductions
may be a flawed approach because of the high dissolved P fraction that occurs in cold climates.
In an initial evaluation of the snowmelt algorithm in northeastern Minnesota, USA, Wang and
Melesse (2005) found that the model was good at predicting monthly, seasonal and annual mean
discharges. However, when a season by season comparison was undertaken, results showed that
if the model performed well during spring then it underperformed in fall and winter. In an
try to reconcile the seasonal deficiencies of the model, LéVesque et al. (2008) compared the
performance of the model using year-long calibrations to using a two-step calibration primarily
relying on summer observations for calibration, with the exception of snowmelt parameters
which are based on winter observations. This approach provided better summer estimates but
failed to significantly improve winter estimates. They also applied a winter-only and summer-
only calibration and found that the summer-only calibration resulted in significant improvements
over the year-long calibration whereas winter-only calibrations resulted in marginal
improvements over the year-long calibration (LéVesque et al. 2008). It is important to note that
neither Wang and Melesse (2005) nor LéVesque et al. (2008) investigated the impacts of
snowmelt specifically on VBS. Additionally, while one of the main features of SWAT is its
usefulness in assessing VBS effectiveness, its VBS model algorithms are based on regression
equations from 22 studies to predict runoff reduction for uniform sheet flow conditions and
exclude concentrated or channelized flow. Channelized flow occurs in buffers in both warm and
cold climates, but in cold climates it is highly dependent on soil moisture conditions prior to
freezing and the occurrence and type of precipitation occurring during the melting period. There
is some evidence that in cold climates, rills are likely to form because of the increased runoff
speed due to a lack of infiltration (Edwards and Burney 1987), but the concentration of sediment
transported is highly dependent on ground cover (i.e. no snow or snow and ice covered) at the
time of precipitation events during the melt period (Starkloff et al. 2017). The runoff reduction
algorithm is based on two factors, runoff load into the VBS from uniform sheet flow, and the
VBS saturated hydraulic conductivity. The runoff reduction level, based only on the uniform
sheet flow portion of runoff, is used to predict sediment reduction which is then used to
determine nutrient reduction (White and Arnold 2009). However, as noted above, relying on
sediment reductions can be a faulty approach because in cold climates, the dissolved P fraction is
usually dominant.
The USDA’s Agricultural Non-Point Source Pollution Model (AnnAGNPS) is another model that is used to predict sediment, water, and nutrient outputs in agricultural landscapes. This watershed scale model requires three main data inputs: i) topographic data; ii) soil and land use data; and iii) climate data. With specific regards to buffers, a GIS-based framework has been developed to integrate plot-scale VBS effectiveness modeling and modeling with AnnAGNPS at the watershed scale (Yuan et al. 2011). This framework is currently focused on integrating VBS into the model for the intention of reducing sediment loading but could become useful with respect to P loading if P inputs can be accurately assessed. In order to use this model, an input file must be created either using a weather generator file from AnnAGNPS or using historical data. Before the model can be validated, model outputs based on the historical data are compared to observed data during a calibration period. After this calibration period, certain sensitive parameters can be altered to help the model better fit the observed data (Das et al. 2008). After these changes to model parameters are completed there is a validation period, where outputs from the calibrated model are compared to observed data. In the single study to determine the effectiveness of this model for predicting water and sediment outputs in a cold climate in Ontario, Canada, Das et al. (2008) found that the simulated runoff was very close to the observed runoff, just 3.3% more than the observed values, but that sediment yield was more varied. The model underpredicted the proportion of sediment yield during the spring, but over-predicted overall sediment yield by 28% during the validation phase. The authors note that AnnAGNPS does not address late-winter and early-spring conditions where rain often falls on top of snow or frozen soils – an important model parameter in cold climates. While this model has been used extensively for sediment and water modeling, its use for nutrient modeling has been limited. One study undertaken in China found that during the calibration period, the model underestimated
loads whereas in the validation period it far overestimated loads, with simulated TP loads of 119.9 kg compared to an observed load of 48.56 kg (Li et al. 2015). However, climate in this watershed is subtropical monsoon and, thus, does not include the uncertainties associated with cold climates which create different uncertainties in modeling.

One model developed to address many of these issues is the Cold Regions Hydrological Model (CRHM), which incorporates a wide range of cold region hydrological processes including blowing snow, interception and sublimation of snow, energy balance snowmelt, and canopy influence on radiation and infiltration into frozen soils (Pomeroy et al. 2007, Fang 2010, 2013). The CRHM has been successfully used to simulate hydrology in catchments in diverse regions around the world including Canada (Dornes et al. 2008; Fang and Pomeroy 2008; Ellis et al. 2010, Mahmood et al. 2017). In the Red River basin of southern Manitoba, Canada, Cordeiro et al. (2017) reported satisfactory representation of snow water equivalent (SWE), evaporation, and simulated soil water volumetric content (VWC) and stream discharge during wet years; years where peak discharge was greater than or equal to median peak discharge. However, the CRHM did not perform well for stream discharge simulation during dry years; years where peak discharge was less than median peak discharge. The authors attributed the poor performance in these years to an inability for the model to account for cracking soils and preferential flow that occurs during dry conditions in this landscape dominated by cultivated clay soils and level topography. They also point to uncertainty in stream discharge records in this region caused by backwater conditions from ice dams as an issue for assessing model performance. Mahmood et al. (2017) used the CRHM to investigate the influences of climatic variability on hydrological processes in the South Tobacco Creek watershed in southern Manitoba, Canada. The model was parameterized using local and regional measurements without calibration. Satisfactory
predictions of spatial patterns of snow depth in the study area demonstrated that the model performed well at simulating snow transport, melting and sublimation processes. Model performance for flow was weaker in wet years and in smaller upstream catchments (Nash Sutcliffe Efficiency = 0.2), but it was adequate for cumulative annual flows (Nash Sutcliffe Efficiency = 0.87). This study concluded that antecedent fall soil moisture, ice lens formation during the snowmelt period, and peak SWE were important factors for simulating snowmelt runoff (Mahmood et al. 2017). The CRHM is purely a hydrological model and at present is not used in predicting the effectiveness of VBS in reducing P transport. However, its modeling of cold climate hydrological processes could be used together with BMP focused models such as SWAT or AnnAGNPS.

There are numerous other models and evaluation tools that are used to determine buffer effectiveness and design including the buffer zone inventory and evaluation form (BZIEF), the BUFFERS Decision Support System (DSS) that relies on both the BZIEF (Deeks et al. 2012) and the modified Morgan-Morgan-Finney soil erosion model (Morgan and Duzant 2008), and a tool specifically designed for the Canadian Prairies (Stewart et al. 2011). These tools are built to be practical and easy to use, as the DSS and Stewart et al. (2011) model include flowcharts for landowners to follow. However, each framework is deficient when specifically focusing on cold climates as neither the BZIEF (Ducros and Joyce 2003) nor the DSS (Deeks et al. 2012) include snowmelt related parameters. The tool designed specifically for the Canadian prairies recognizes the uniqueness that prolonged frozen temperatures can have on buffers, but still assumes that under prairie frozen soil conditions, trapping of soluble nutrients is primarily achieved through infiltration and that sediment trapping by frozen buffers is still effective (Stewart et al. 2011). Under certain conditions, the assumptions made with regards to buffer effectiveness in trapping
Sediments may be true, but this is likely not always the case. Vegetative cover is the most important variable determining infiltration into frozen soils, and infiltration into frozen cultivated crop soils is often lesser than infiltration into frozen soils under permanent vegetation (Edwards and Burney 1987). However, numerous other variables including soil temperature, depth of frost, and soil water content will determine if infiltration occurs (Ban et al. 2016). Thus, the assumptions made by Stewart et al. (2011) may be true in some situations, but results from Sheppard (2006) and Habibiandehkordi et al. (2017) have found that decreased surface roughness over winter reduces trapping in the VBS. The potential ability for snowmelt infiltration should not be ignored in frozen conditions, but understanding the aforementioned variables and infiltration processes during the frozen season and snowmelt period are of importance (Deelstra et al. 2009), and should also be included in the tool. The BZIEF, DSS and the Stewart et al. (2011) tools are useful because of their ease of use but lack the inclusion of specific parameters that are needed for dealing with VBS in cold climates. The inclusion of cold climate parameters within these frameworks is important because it would create a more practical tool for those who are working on a field scale or those who do not have the resources to use more complex models.

5 Further research needs

The largest research gap is perhaps simply that there has not been an equal amount of research conducted in cold climates as there has in warm or temperate climates on the effectiveness of VBS, especially during the snowmelt period. Additionally, of the research completed thus far, much of it has been under controlled greenhouse and laboratory conditions or at a plot scale. These smaller scale projects are important for understanding cold climate P dynamics in buffer vegetation, but larger scale and longer duration studies are needed to begin to
understand how these dynamics change spatially (i.e. on a catchment scale) and temporally (i.e. high and low snowpack years). This is particularly true in the context of changing climate where the amount of FTCs that vegetation will be subjected to is likely to increase (Henry 2008), and annual snowpack and soil moisture levels may decrease significantly (Gan 2000).

Another focus of the research currently being undertaken to determine the effectiveness of VBS in cold climates is on the potential for P release from vegetation, and a growing number of studies are also considering the potential for release from P-enriched soils. This includes soils in unmanaged VBS that have been trapping sediments from adjacent fields from multiple growing seasons, leading to a build-up of P enriched soils at the surface layer, as well as soils enriched in P from prior land use activities, namely a buildup of P from past fertilizer application. Microbial activity has also been identified as a potential mechanism by which P can be released from soils, but research to quantify the potential loss of P through this mechanism has been limited (Stutter et al. 2009). Additionally, because in cold climates microbial activity is limited during the spring snowmelt due to frozen soils, this mechanism would be limited to the relatively short growing season, a consideration that should be taken into account in future field studies.

Determining the ideal species to be planted in buffers is also an important area where more field based research is needed as prior studies have shown both that the residue from perennial forage crops increased FWMCs of both TDP and TP compared to residue from annual crops (Liu et al. 2014), but also that annual crops released greater concentrations of DRP (Cade-Menun et al. 2013) and TP (Liu et al. 2013) than perennials. Furthermore, different species of perennials will release significantly different concentrations of P (Øgaard 2015). Finally, while vegetation has been identified as an important contributor of P because of release from senesced vegetation, further research on the ability for soils to release P and the interaction between soils and
vegetation are also needed. In the aforementioned study undertaken in Wisconsin, USA, Roberson et al. (2007) found that concentrations of SRP extracted from alfalfa that had undergone freezing or drying increased as soil test P concentrations increased. However, research undertaken in Saskatchewan, Canada, to determine the potential of numerous species of vegetation to release P also included leaching from the active layer of soil (0-5 cm) and results from soil leaching analysis did not follow the trend of the Roberson et al. (2007) study. Elliott (2013) found that release from soils and wheat stubble were similar, but that frozen and thawed samples collected from winter wheat released significantly more nutrients than the soils associated with winter stubble or with winter wheat. The soils in that study did not have high concentrations of soil P and the author acknowledges that soils enriched in P, as many soils in agricultural landscapes are, could potentially release more nutrients than those in this study. Nevertheless, the interaction between soils and buffer vegetation is likely an important dynamic for P release and while these two studies begin to illuminate the impact of this interaction, further research is needed.

Finally, while there has been progress in integrating cold climate conditions and the impact of buffer strips into various runoff models, there has been a lack of validation studies that include both of these conditions and their effect on nutrient loading. Most studies include inputs of either cold conditions or buffers when utilizing the models and furthermore, they focus primarily on predicting sediment transport and deposition or determining runoff and streamflow in response to specific inputs. Significantly more research which includes both variables (i.e. cold climate conditions and implementation of buffers) to predict nutrient runoff is needed.
6 Conclusions and Management Recommendations

Buffers have long been utilized as a BMP in agricultural landscapes because of their perceived proven effectiveness in filtering sediments and nutrients under certain climatic and landscape conditions. However, as this review illustrates, they are not always effective P sinks in landscapes in cold climates. The function and effectiveness of buffers implemented in cold climates cannot be assumed to be the same as those of buffers implemented in more temperate climates due to the reduced ability for vegetation to trap sediments, slow overland flow, encourage infiltration, or take up excess nutrients. As noted by Roberts et al. (2012), rather than being the final sink for P, VBS may function more as part of a ‘modifying loop’ where PP can be transformed to DP. Another possibility, as the research collated in this review shows, is that VBS can also be a significant source of P under certain situations and conditions.

Research specifically focused on buffers in cold climate during the spring runoff period has shown efficiencies of P removal ranging from -36% to +89%, a range that is likely the product of numerous other factors influencing buffer efficiency including slope, concentrated flow, antecedent soil conditions, buffer width, and vegetation species and density. However, there is more consistency and consensus when specifically looking at the potential for vegetation to release P. While the concentration of P released varies based on species, pre-extraction conditions, and the extraction procedure itself, it is clear that buffer vegetation can become a source of P. Whereas substantial evidence in North America points to their lack of effectiveness in reducing P transport during the spring snowmelt, results across Sweden, Norway and Finland are far less consistent likely due to the subtle but important climatic and landscape differences between the two regions. In addition to the uncertainties of their ability to effectively remove P
in cold climates, this review has made clear that there is still much that is unknown about what
the best species and management practices are for VBS, if they are to be implemented at all.

More research focusing on cold climate buffers at a field and catchment scale is needed, but
there is clear evidence that buffers can be a source of P and thus, buffer management after
implementation should be considered. A management strategy for both vegetation and soils
should be considered at the implementation stage and continually revisited as the VBS becomes
more established. One strategy commonly considered in cold climates where FTCs occur is to
harvest the vegetation and remove it from the landscape. This strategy would be beneficial to
landowners as the land planted as a buffer could be cut multiple times for hay, and be beneficial
for water quality as the concentrations of P released from vegetation residue would likely be
reduced compared to the dead whole plant (Stutter et al. 2009). Additionally, if the intention of
buffers is to reduce P loading through plant uptake, then harvesting the shoots of this vegetation
is important because it would help maintain low levels of soil P (Kelly et al. 2007). The use of
harvesting as a management strategy in buffers is one that has been discussed widely, and though
there have only been a few studies determining its effectiveness, thus far the results have shown
it to be an effective strategy in reducing P loads, and in particular, soluble P loads (Uusi-Kämppä

One potential issue that could arise with using harvesting as a management strategy is that it
would reduce soil cover over winter and could lead to soil erosion and loss of nutrients in the
spring in much the same way that cropped fields do, which is the process that buffers were
intended to protect against. For this reason, additional field scale research is needed to determine
the potential benefits and problems with this management strategy. Furthermore, it is important
that the vegetation harvested from the buffer be treated in an appropriate way so as to avoid other
problems. For example, dumping of the harvested vegetation adjacent to the buffer (e.g., between the field and the buffer) or near a preferential flow pathway is likely to create a new point-source of P due to release from the dead vegetation.

As management strategies such as harvesting and removing vegetation become more commonly implemented, the ability of P to be released from soils will need to be considered as numerous studies have shown that soils with high concentrations of P are at risk of releasing P in much the same way that vegetation can after freezing and thawing (Bechmann et al. 2005). Thus, it is also important to study how concentrations of soil P in VBS compare to soil P in the field and what the potential is for P release from soils. This is particularly true because VBS are potentially trapping soil eroded from upslope fields for years and because rapid uptake of P by perennial vegetation can eventually plateau and even decline (Kelly et al. 2007; Dosskey et al. 2010). Additionally, when considering the potential for harvesting and its effect on soils, it must also be considered how it could potentially alter the biological and chemical processes occurring in soils. Harvesting vegetation would have an impact on both soil moisture and soil temperature, which have been shown to change the P retention capacity of buffers. Bare soils, like those that would result from harvesting vegetation, are more susceptible to earlier freezing and freezing to a greater depth because of their lack of insulating layer and are also likely to be earlier to thaw in the spring (Fu et al. 2017). This could have implications for P fixation from microbial activity and adsorption, and for infiltration of runoff water in the spring.

Designing VBS tailored to specific landscapes – even specific fields – should also be considered when implementing VBS to maximize P retention and utilization. Various VBS characteristics, including width, stem density, and species, have proven to be important in determining effectiveness, but should be carefully considered before implementation based on
specific characteristics of the field the VBS will be employed in. And, while much of the data needed to tailor VBS to specific fields is available, there are minimal resources for landowners to obtain and use that data in planning their VBS. Additionally, implementation and management of field-specific VBS can be expensive and time consuming, and in many regions there is little to no funding available to landowners for this purpose. In addition to implementing a VBS, in some landscapes, physically modifying the land by smoothing the surface could be useful to increase the dispersion of runoff water and reduce concentrated flow. This would increase retention of runoff water and also increase the potential for vegetation to filter sediments and nutrients.

There are other BMPs used in agricultural landscapes that focus on upland cultivated fields including conservation tillage and the use of cover crops (Flaten 2016). However, when focusing exclusively on the reduction of P loss to surface waters, both conservation tillage and cover cropping aim to reduce particulate P loss which, as this paper has outlined, is less of the problem than dissolved P, particularly in the North American prairie region. Additionally, a study by Tiessen et al. (2010) found that after conversion from conventional to conservation tillage P concentrations in runoff increased by 42% during the snowmelt period, most of which was dissolved P. This work is supported by numerous studies cited in sections 3.4 and 3.5 that showed dissolved P loss from vegetation residue. Thus, much like buffers, the implementation of other BMPs need to be evaluated in cold climates, and also should be evaluated with regards to other potential benefits these practices can have on water quality, namely the reduction of erosion and of other nutrients including nitrogen (Flaten 2016).

Vegetated buffers strips – or vegetated filter features more generally – have the potential to help land owners, farmers and watershed managers reduce the rate and/or magnitude by which water, sediment and associated chemicals like nutrients and pesticides are delivered to surface

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waters by providing a mechanism to control the connectivity between land and waterways.

However, the design, implementation and management of such features require careful consideration, especially in cold climates where conditions may influence how – and when – they function (e.g. Figure 1). They may not always be the best approach to protect surface waters in intensive/extensive agricultural landscapes. As such, buffers should be considered as one option, or tool, as part of a wider landscape-based approach to the management of watersheds.

7 Acknowledgements

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8 References


https://mc06.manuscriptcentral.com/er-pubs


Gan, T.Y. 2000. Reducing vulnerability of water resources of Canadian prairies to potential


practice effectiveness for phosphorus pollution control. J. Soil Water Conserv. 60(1): 1–
10.

characteristics and trends in a small agricultural watershed: South Tobacco Creek,
Manitoba (Saskatoon, SK, Canada: Environment Canada).


Uncertainties in vegetated buffer strip function in controlling phosphorus export from
18382. doi: 10.1007/s11356-017-9406-6.

losses under three different tillage systems. Soil Tillage Res. 57: 93–100.

Henry, H.A.L. 2008. Climate change and soil freezing dynamics: historical trends and projected

Hickey, M.B.C., and Doran, B. 2004. A review of the efficiency of buffer strips for the
311–317.


Liu, X., Zhang, X., and Zhang, M. 2008. Major factors influencing the efficacy of vegetated
buffers on sediment trapping: A review and analysis. J. Environ. Qual. 37(5): 1667. doi:


Shirmohammadi, eds. (Boca Raton, FL USA: CRC Lewis Publishers), pp. 305–328.

responses to climatic variability in a cold agricultural region. Hydrol. Processes 31(4):


McConkey, B.G., Nicholaichuk, W., Steppuhn, H.and Reimer, C.D. 1997. Sediment yield and
40.

prairie watersheds. J. Hydrol. Eng. 21(5).

management practices in a cold-climate prairie watershed: Assiniboine River watershed,

Miller, M., Beauchamp, E., and Lauzon, J. 1994. Leaching of nitrogen and phosphorus from the


Nielsen, P.V., and Hansen, A.C. 1993. Buffer zones and phosphorus supply to Danish surface waters (Hedeselskabet, Denmark).


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Table 1: Summary table of studies in cold climates that include a determination of the type of runoff (snowmelt vs. rainfall) and or the dominant type of phosphorus in snowmelt runoff.

Table 2: Summary table of field research undertaken to determine the effectiveness of vegetative buffer strips (VBS) in reducing phosphorus delivery to surface waters in cold climates.

Table 3: A comparison of 10 studies that incorporated freeze-thaw cycles in experiments on leaching and runoff potential of various forms of dissolved phosphorus from vegetation. A list of abbreviations is found at the end of the table.

Figure 1a: A conceptual diagram illustrating the various mechanisms buffers use to reduce sediment and nutrient loading in warmer climates where runoff events are rainfall driven and occur during the growing season, when soils are unfrozen. In these ideal conditions, various processes in the soil can immobilize P, buffer vegetation is actively taking up P, and buffers act as a sink for sediments, nutrients and other contaminants such as pesticides.

Figure 1b: A conceptual diagram illustrating the reduced effectiveness of buffers in cold climates, when the buffer is covered in snow and/or ice and when soils and vegetation are frozen. In this scenario, the buffer is not always a sink for sediments and nutrients but can potentially become a source due to leaching of P from the buffer vegetation and the inability for infiltration to occur or for sediments to be trapped.

Figure 2: Map of North America based on the Köppen-Geiger climate classification (modified from Peel et al. 2007). Stars denote study sites included in the review.

Figure 3: Map of Europe based on the Köppen-Geiger climate classification (modified from Peel et al. 2007). Stars denote study sites included in the review.
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Table 1: Summary table of studies in cold climates that include a determination of the type of runoff (snowmelt vs. rainfall) and dominant type of P in runoff

<table>
<thead>
<tr>
<th>Reference</th>
<th>Location</th>
<th>Snowmelt Runoff (%)</th>
<th>Particulate or Dissolved?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nicholaichuk 1967</td>
<td>Saskatchewan, Canada</td>
<td>85</td>
<td>N/A</td>
</tr>
<tr>
<td>Gill et al. 1998</td>
<td>Alberta, Canada</td>
<td>&gt;80</td>
<td>N/A</td>
</tr>
<tr>
<td>Ontkean et al. 2005</td>
<td>Alberta, Canada</td>
<td>2-76</td>
<td>Dissolved</td>
</tr>
<tr>
<td>Glozier et al. 2006</td>
<td>Manitoba, Canada</td>
<td>&gt;66</td>
<td>Dissolved</td>
</tr>
<tr>
<td>Little et al. 2006</td>
<td>Alberta, Canada</td>
<td>N/A</td>
<td>Dissolved</td>
</tr>
<tr>
<td>Sheppard et al. 2006</td>
<td>Manitoba, Canada</td>
<td>N/A</td>
<td>Dissolved</td>
</tr>
<tr>
<td>Little et al. 2007</td>
<td>Alberta, Canada</td>
<td>&gt;90</td>
<td>N/A</td>
</tr>
<tr>
<td>Deelstra et al. 2009*</td>
<td>Finland, Norway, Lithuania, Sweden, Europe</td>
<td>15-70</td>
<td>N/A</td>
</tr>
<tr>
<td>Tiessen et al. 2010</td>
<td>Manitoba, Canada</td>
<td>80-90</td>
<td>Dissolved</td>
</tr>
<tr>
<td>Cade-Menun et al. 2013</td>
<td>Saskatchewan, Canada</td>
<td>N/A</td>
<td>Dissolved</td>
</tr>
</tbody>
</table>

Table 2: Summary table of field research undertaken to determine the effectiveness of vegetative buffer strips (VBS) in reducing phosphorus delivery to surface waters in cold climates

<table>
<thead>
<tr>
<th>Reference</th>
<th>Location</th>
<th>VBS Width</th>
<th>Vegetation type</th>
<th>Parameter measured</th>
<th>Reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheppard et al. 2006</td>
<td>Manitoba, Canada (2 years)</td>
<td>5-50 m</td>
<td>Grass, sedge, natural vegetation</td>
<td>Ortho-P*, TDP†, TP‡</td>
<td>-2% to +40%</td>
</tr>
</tbody>
</table>

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<table>
<thead>
<tr>
<th>Study</th>
<th>Location</th>
<th>Area (m)</th>
<th>Vegetation Description</th>
<th>Parameter</th>
<th>Effect Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Habibiandehkordi et al. 2017</td>
<td>Manitoba, Canada</td>
<td>10 m</td>
<td>Grass, sedge, natural vegetation</td>
<td>TDP</td>
<td>-50% to +19% (snowmelt) -250% to +50% (rainfall)</td>
</tr>
<tr>
<td>Syversen 2005</td>
<td>Norway, Europe</td>
<td>5 and 10 m</td>
<td>Grass</td>
<td>TP</td>
<td>37% to 81%</td>
</tr>
<tr>
<td>Uusi-Kämppä 2005</td>
<td>Finland, Europe</td>
<td>10 m</td>
<td>Grass (GB) Scrub plants, trees, hay and flowers (VB)</td>
<td>DRP§</td>
<td>-110% spring (VB), No change spring (VB and GB) 15% autumn (VB and GB), 40% in both plots</td>
</tr>
<tr>
<td>Syversen 2002</td>
<td>Norway, Europe</td>
<td>5 and 10 m</td>
<td>Grass</td>
<td>TP</td>
<td>76% 5 m buffer 89% 10 m buffer</td>
</tr>
<tr>
<td>Uusi-Kämppä and Yläranta 1992, 1996</td>
<td>Norway, Europe</td>
<td>10 m</td>
<td>Grass</td>
<td>DRP TP</td>
<td>14% 38%</td>
</tr>
<tr>
<td>Uusi-Kämppä and Yläranta 1992, 1996</td>
<td>Finland, Europe</td>
<td>10 m</td>
<td>Perennial grasses, shrubs, bushes, trees</td>
<td>DRP TP</td>
<td>-64% 27%</td>
</tr>
<tr>
<td>Syversen 1996, 1997</td>
<td>Norway, Europe</td>
<td>5 and 10 m</td>
<td>Grass</td>
<td>TP</td>
<td>88% 5 m buffer 96% 10 m buffer</td>
</tr>
<tr>
<td>Ulén 1988</td>
<td>Sweden, Europe</td>
<td>5 m</td>
<td>Grass</td>
<td>TP</td>
<td>-36%</td>
</tr>
<tr>
<td>Nielsen and Hansen, 1993</td>
<td>Denmark, Europe</td>
<td>2 and 6 m</td>
<td>Grass</td>
<td>TP</td>
<td>65% 2 m buffer 97% 6 m buffer</td>
</tr>
</tbody>
</table>

*Orthophosphate
† Total Dissolved Phosphorus
‡ Total Phosphorus
§Dissolved Reactive Phosphorus
Table 3: A comparison of 10 studies that incorporated freeze-thaw cycles in experiments on leaching and runoff potential of various forms of dissolved phosphorus from vegetation. A list of abbreviations is found at the end of the table.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Growing conditions: (Lab/Field)</th>
<th>Plant Material</th>
<th>Freeze Thaw treatment Temp°C (duration-hrs)</th>
<th>Shaking</th>
<th>Extraction Method</th>
<th>Selected Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>*Timmons et al. 1970</td>
<td>Field Minnesota, USA shoots</td>
<td>Shoots</td>
<td>1. Fresh material leached immediately. Followed by two cycles of -16°C (16-24), thaw (.25 hrs), leach (A) 2. 3 cycles of: -16°C (16-24), thaw (0.25), leach (B) 3. -16°C (16-24), thaw (0.25), leach. Followed by -16°C (16-24), thaw, +65°C (8), leach, -16°C (16-24), thaw, leach (C)</td>
<td>No shaking</td>
<td>20-25 g samples were soaked in 300 mL DI for 1 hr. followed by percolation of 700 mL DI through sample for 1.5 hrs.</td>
<td>-Values are a sum from three leachings for each of the treatments</td>
</tr>
<tr>
<td>Miller et al. 1994</td>
<td>Field Ontario, Canada shoots</td>
<td>Shoots</td>
<td>1. -18°C (N/A) 2. -18°C (N/A)/ 30°C</td>
<td>No shaking</td>
<td>Biomass from 2.25 m² area frozen or frozen and dried, subjected to a 2 cm/hr. or 4 cm/hr. rainfall event</td>
<td>1. 14-32% SP leached 2. 22-33% SP leached <strong>Used a weighted mean concentration</strong></td>
</tr>
<tr>
<td>Bechmann et al. 2005</td>
<td>Lab Shoots</td>
<td>Shoots</td>
<td>-18°C (12)/+10°C (12) FTCs: 0,1,2,4,6,8</td>
<td>Time: 1hr. Rate: Not reported Temp: 25°C</td>
<td>0.4 g fresh biomass added to 80 mL of DI</td>
<td>0FTCs: &lt;1% of plant TP released as WEP 1FTC: 40% of plant TP released as WEP 8 FTC: &gt;100% of plant TP released as WEP</td>
</tr>
<tr>
<td>Roberson et al. 2007</td>
<td>Field Wisconsin, USA shoots - alfalfa</td>
<td>Shoots</td>
<td>1. Fresh samples (No FT) 2. -5°C (24) 3. -5°C (24)/Room temperature (24)</td>
<td>Time: 1hr. Rate: Not reported Temp: Not reported</td>
<td>150 g fresh biomass added to 1300 mL DI water</td>
<td>14% of plant TP released as SP 18% of plant TP released as TSP</td>
</tr>
<tr>
<td>Saleh 2008</td>
<td>Field Manitoba, Canada residues</td>
<td>Samples were soaked at room temperature (24), then frozen at -15°C (24), then thawed (36)</td>
<td>Gentle rolling of samples in DI before and after FTC</td>
<td>0.0625 m³ equivalent of residues added to 3.7 L of DI</td>
<td>Water extractable SRP in frozen/thawed residue: 2.3 mg/L</td>
<td></td>
</tr>
<tr>
<td>Räty et al. 2010</td>
<td>Field Shoots</td>
<td>Natural conditions</td>
<td>Time: 18 hr. Rate: 250 rpm</td>
<td>0.5 g dried and ground plant sample added to</td>
<td>Average of 67% of TP was MRP</td>
<td></td>
</tr>
<tr>
<td>Location</td>
<td>Source</td>
<td>Type of Residue</td>
<td>Temperature/Condition</td>
<td>Extractions Method</td>
<td>Time/Rate/Temperature</td>
<td>Notes</td>
</tr>
<tr>
<td>-----------------</td>
<td>------------</td>
<td>-----------------</td>
<td>-----------------------</td>
<td>--------------------</td>
<td>-----------------------</td>
<td>----------------------------------------------------------------------</td>
</tr>
<tr>
<td>Finland</td>
<td><em>Elliott 2013</em></td>
<td>Crop and plant residues</td>
<td>-5°C/+9°C/-5°C (diurnal cycles for 3 days) followed by 2 days of +5°C</td>
<td>No shaking</td>
<td></td>
<td>20 mm SWE overlain 0.04 m² of residue sample. After snow had all melted, meltwater was decanted and analysed. Residues released 6-15 mg/L P (&lt;1% of TP contained in residue biomass)</td>
</tr>
<tr>
<td>Saskatchewan, Canada</td>
<td>Liu et al. 2013</td>
<td>Roots and shoots</td>
<td>-18°C (62)/+18°C (10) 2. +4°C (20) 3. -18°C (10)/+18°C (10) 4. -18°C (10)/+18°C (10) 1. Four consecutive water extractions occurred every 5 hours 2. Single water extraction 3. Four consecutive water extractions occurred every 5 hours 4. Single water extraction after each FTC</td>
<td>All Extractions: 2.0 g fresh biomass in 100 mL of DI water.</td>
<td>1 hr. 16 rpm Room temperature</td>
<td>Shoots: WEP ranged from 10 mg/kg on fresh material to 1600 mg/kg from extraction method 4 (see adjacent column) Roots: Released on average 43% less TP than shoots. No significant difference between extraction methods</td>
</tr>
<tr>
<td>Manitoba, Canada</td>
<td><em>Liu et al. 2014</em></td>
<td>Crop and perennial forage residue</td>
<td>Samples were soaked at room temperature (24), then frozen at -20°C (24), then thawed overnight</td>
<td>Hand shaken for 30 s before freezing, gentle rolling after thaw</td>
<td>0.0625 m² equivalent of residues added to 1.875 L of DI</td>
<td>Perennial forage released significantly more WEP than annual crop residues.</td>
</tr>
<tr>
<td>Norway</td>
<td>Øgaard 2015</td>
<td>Shoots</td>
<td>-10°C (12)/+5°C (12) FTC</td>
<td>Time: 1 hr. Rate: 75 rpm Temp: Room temperature</td>
<td>3.0 g fresh plant material added to 80 mL distilled water</td>
<td>67-82% of TP was DRP 1% of plant TP was released after 7 FTCs in timothy.</td>
</tr>
<tr>
<td>Norway</td>
<td>Øgaard 2015</td>
<td>Shoots</td>
<td>Natural conditions</td>
<td>Time: 1 hr. Rate: 75 rpm Temp: Room temperature</td>
<td>2.0 g fresh field samples added to 90 mL water</td>
<td>-55-91% of TP was DRP 45% of plant TP was released after entire winter season</td>
</tr>
</tbody>
</table>

**DI**, deionized water  
**FTCs**, freeze-thaw cycles  
**TP**, total phosphorus
**TSP**, total soluble phosphorus

**DRP**, dissolved reactive phosphorus

**SRP**, soluble reactive phosphorus

**WEP**, water extractable phosphorus

**SWE**, snow water equivalent

* denotes a runoff study which incorporates the impact of FTCs on P release