Soluble Phosphorus Losses in Spring Snowmelt Runoff in the Northern Great Plains*

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ABSTRACT

The development of water quality beneficial management practices (BMPs) requires detailed information about the effects of landscape and climate on the processes and management practices that affect P export from agricultural land to surface water bodies. However, most of the information on P behavior and transfer has been developed for areas where P losses are dominated by soil erosion caused by rainfall runoff. This information may not be pertinent to the Northern Great Plains, with its relatively flat agricultural land base, cold and dry climate, and snowmelt dominated runoff. The relatively low rates of erosion in this region create a situation where most of the P in runoff is in a dissolved form; therefore, erosion control practices will probably do little to reduce P loss. Recent research in the Canadian Prairies confirms that conservation tillage, perennial forages and vegetated buffer strips may not be very effective for reducing P losses in this region. Conversely, water management practices that allow nutrient-rich snowmelt runoff water to be retained and used upstream in our watersheds show considerable promise for reducing P loss from Prairie farms. However, that practice must also be employed carefully, since submergence of some soils can release large amounts of soluble P to overlying floodwater when the soils become anaerobic.

CONCERNS FOR PHOSPHORUS IN THE ENVIRONMENT

Increasing P enrichment of surface water bodies and the subsequent decline in water quality is a concern across North America, and the Canadian Prairie province of Manitoba is no exception. This increase in availability of P in aquatic environments increases the growth of algae, surface scums, followed by the depleted oxygen concentrations, foul odours, sedimentation, fishkills and release of algal toxins (Schindler, 1977; Sharpley et al., 1994). Within Manitoba, the greatest public concern is for the health of province's largest lake, Lake Winnipeg. This lake is the sixth largest freshwater lake in Canada and the tenth largest in the world. However, the health of this aquatic ecosystem has deteriorated over the past three decades, with evidence pointing to excessive nutrient enrichment from P as the primary cause (Lake Winnipeg Stewardship Board, 2006).

Similar to many other watersheds around the world, the majority of phosphorus flowing into Lake Winnipeg comes from nonpoint sources, including natural ecosystems, atmospheric deposition, and agricultural and urban activities (Lake Winnipeg Stewardship Board, 2006). Nevertheless, to reduce agriculture's portion of P that flows into Lake Winnipeg, it is critical to improve our understanding of how phosphorus losses in the Lake Winnipeg watershed are related to soil characteristics, topography, and local climatic conditions, as well as the crop, soil, nutrient, and water management practices used for agricultural production in the watersheds.

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IMPORTANCE OF SNOWMELT RUNOFF FOR PHOSPHORUS LOSS IN THE NORTHERN GREAT PLAINS

In cold-climate regions, especially those with a semi-arid or sub-humid climate, such as the Canadian Prairie region of the Great Plains, snowmelt runoff often exceeds rainfall runoff on an annual basis (Nicholaichuk, 1967; Granger and Gray, 1990; Chanasyk and Woytowich, 1986; Granger et al., 1984; Glozier et al., 2006; and Little et al., 2007). As a result, the loss of nutrients during the snowmelt period can be substantial, as also observed in other cold-climate regions of North America (Hansen et al., 2002) and Northern Europe (Rekolainen et al., 1997). In the Canadian Prairies, Glozier et al. (2006) reported that more than two thirds of the runoff flow and P export in south-central Manitoba occurred during the snowmelt period, with the majority of P exported in dissolved forms. Additional studies from Alberta also report that >90% of annual runoff was generated during the spring snowmelt (Little et al., 2007) and that dissolved P in snowmelt waters is the dominant form of P export (Ontkean et al., 2005; Little et al., 2006). Runoff studies on cropland and pasture in Saskatchewan have also demonstrated that dissolved P is the dominant form of P exported in runoff in this region (Cade-Menun et al., 2013).

The relatively large proportion of dissolved P in runoff from snowmelt has also been observed in Northern Europe (Ulen et al., 2007) and is partly due to the low kinetic energy associated with snowmelt compared to falling rain, as well as the frozen state of the soils that usually occurs during snowmelt (Rekolainen et al., 1997). Therefore, snowmelt runoff is usually less erosive than rainfall-induced runoff (Ginting et al., 1998; Ulen, 2003). However, due to the relatively high proportion of runoff volume from snowmelt compared to rainfall runoff, soil losses due to snowmelt in these regions are often greater than those due to rainfall (Chanasyk and Woytowich, 1987; van Vliet and Hall, 1991; McConkey et al., 1997).

Greater losses of soluble P during snowmelt are also due to the release of nutrients from plant residues on the soil surface (Timmons et al., 1970; Rekolainen, 1989; Miller et al., 1994; Ulen, 1997; Elliott, 2013). This release of nutrients from plant residues during snowmelt is especially important in cold-climate regions where freeze–thaw cycles increase cell rupture and release water soluble nutrients (Bechmann et al., 2005; Roberson et al., 2007; Saleh, 2008).

EVALUATION OF WATER QUALITY BMPS FOR SNOWMELT RUNOFF-DOMINATED SITUATIONS

In order to reduce P losses from agricultural land in the Northern Great Plains, the processes and practices than control P loss in this region must be understood. Without this knowledge, the BMPs encouraged by public education, incentives, and regulations may be ineffective and even counter-productive. For example, the relatively large proportion of P lost in the form of dissolved P, rather than particulate P indicates that erosion is not the major process that accounts for P loss from agricultural land in this region. This conclusion is also supported by the extremely poor relationship between erosion and TP concentrations in Manitoba watersheds (Salvano, 2009). Therefore, the conventional notion that controlling erosion will automatically control P loss is not necessarily valid for this region.

To help resolve this issue, recent research in the Canadian Prairies and elsewhere is providing some insight about which BMPs may or may not work for reducing P losses from agricultural land to surface water. A few examples of that research are summarized as follows.

Conservation Tillage

Conservation tillage provides many agronomic, economic and environmental benefits in the Northern Great Plains. In more temperate and humid areas with steeper slopes, this practice is also effect for reducing losses of sediment and nutrient from agricultural fields. However, the effect of conservation tillage on sediment and nutrient export in snowmelt-dominated climates is not well documented.

A long-term paired watershed study was recently conducted in Southern Manitoba to compare sediment and nutrient losses from a conventional watershed and a conservation tillage watershed (Tiessen et al., 2010). Concentrations of dissolved N and P were typically greater during spring snowmelt than during summer rainfall events, whereas concentrations of sediment and particulate N and P were greatest during rainfall events. However, since total runoff was dominated by snowmelt, most nutrient losses occurred during snowmelt. After accounting for the inherent differences between these two watersheds, conservation tillage reduced the export of sediment in runoff by 65% and concentrations and export of N by 41 and 68%, respectively, relative to conventional tillage. However, conversion to conservation tillage increased concentrations and exports of P increased by 42 and 12%, respectively, with dissolved P accounting for the majority of the exported P. Similarly, in a subsequent study on the same paired watershed, periodic fall tillage in the "conservation tillage" watershed reduced losses of dissolved P and total P in the subsequent snowmelt runoff period by 56% and 42%, respectively (Liu et al. 2014a).

These results are not unique. Many other researchers have reported that conservation tillage increases the loss of dissolved P from agricultural watersheds (Baker and Laflen, 1983; Sharpley and Smith, 1994; Gaynor and Finlay, 1995; Ulen et al., 1997; Ginting et al., 1998; Hansen et al., 2000; Hansen et al., 2002; Puustinen et al., 2005; Harmel et al., 2006; Uusitalo et al., 2007). However, in most of these other studies the majority of total P (dissolved plus particulate P) transported from conventionally tilled land was in the particulate form, so total P losses were reduced with conservation tillage, due to reduced soil erosion.

These results suggest that BMPs designed to improve water quality by reducing sediment and sediment-bound P export from agricultural fields and watersheds can be less effective and perhaps even counter-productive in cold, dry regions where nutrient export is primarily snowmelt driven and in the dissolved form. These results also show that management practices that are effective in reducing losses of one nutrient, such as N, may not be effective in reducing losses of another nutrient, such as P.

Perennial Forages, Cover Crops and Vegetated Buffers

Perennial forages, cover crops and vegetated buffers are BMPs that are often promoted for using vegetation to reduce soil erosion and nutrient losses and improving water quality. However, all of these practices are vulnerable to the same processes that nullify the benefits of conservation tillage as a BMP for reducing P loss in snowmelt runoff systems. With most of the runoff P in dissolved form, the dead or dormant vegetation is as likely to be a source as a sink for P during snowmelt.

Runoff losses of P from native prairie and other perennial forage systems can be substantial, given the rich layer of vegetation on the soil surface that accumulates in these systems. For example, total P concentrations in spring and summer runoff from native prairie near Stavely, Alberta ranged from 0.10 to 0.52 mg/L (Little et al., 2007), 5-26 times greater than the 0.02 mg/L threshold for eutrophication. Total P concentrations in runoff from native prairie in west central Minnesota were also high, averaging 0.50 mg/L (Timmons et al., 1970). In a nearly completed eight-year paired watershed study in Southern Manitoba, total runoff losses of P from alfalfa forage land were 160% greater than those from annual crop land, due in large part to a 221% increase in losses of dissolved P (Liu et al. 2014b). Most of this increase in P loss is probably due to the leaching of water soluble P from thawing vegetative residues during snowmelt. In two years of the study period, samples of alfalfa collected from these watersheds in late fall released an average of 4 kg P/ha after freezing and thawing, whereas release of water soluble residue P from conventionally tilled cropland averaged 0.15 kg P/ha (Saleh 2008). However, if field conditions enable frozen vegetative tissue to be thawed and vegetative P to be leached by modest rainfall events into unfrozen soil prior to the main winter freezing event, losses of vegetative P to spring runoff might be minimized. For example, in Wisconsin studies, Roberson et al. (2007) observed large losses of vegetative P from alfalfa to runoff in rainfall simulation studies after freezing, but did not measure similarly large runoff losses in field studies.

Cover crops may also contribute substantial amounts of dissolved P to snowmelt runoff. In a rainfall simulator study with annual ryegrass as a cover crop, total P losses in runoff were seven times greater from the cover crop treatment than from bare soil after the soil and cover crop were exposed to freezing and thawing (Bechmann et al. 2005). The main reason for this increase in P loss was a 69-79 fold increase in dissolved P losses after the freezing and thawing event. In another simulated snowmelt runoff study, Elliott measured much more dissolved P loss from vegetation that was green and growing prior to freezing than from vegetation that had matured and died prior to freezing (Elliott 2013). However, as mentioned earlier regarding the alfalfa studies by Roberson et al. (2007), modest rainfall events after the growing crop is initially frozen may enable water soluble vegetative P to be leached into unfrozen soil, reducing the risk of P loss in runoff from the cover crops under field conditions.

Vegetated buffers have also proven to be relatively unreliable for reducing P loss to surface water. In three studies that monitored 22 vegetated buffer sites in seven study areas across southern Manitoba there were no significant reductions in P concentrations as runoff passed through strips (Sheppard et al. 2012). These results are similar to those from an earlier but smaller study in southern Manitoba (Sheppard et al. 2006). Also, in a vegetative filter strip study in Vermont, Schellinger and Clausen (1992) found that the filter strip reduced nutrient loading during the growing season, but often increased nutrient loading in the fall, winter and spring periods.

Holding Ponds, Small Dams and Reservoirs

Given the challenges of preventing or intercepting snowmelt losses of P within fields or at the edge of fields, researchers in Manitoba and elsewhere are looking towards direct management of runoff water using retention basins, small dams and reservoirs. In a farm scale assessment of water quality BMPs, Li et al. (2011) measured a 38% reduction in P loss from a farm scale watershed in Manitoba due to implementation of a variety of BMPs. Over half of this reduction was probably due to diverting runoff from cattle pens into a holding pond, where it was subsequently used for irrigation. Another study in the same area measured a 10-15% reduction in P export from the watershed as a result of using small dams to retain runoff water in reservoirs (Tiessen et al., 2011). If this nutrient-rich water is used for irrigation during dry periods, such as those that occur often in the Northern Great Plains region, this practice may offer benefits for increasing crop production as well as improving water quality.

However, the retention of water on agricultural land must be employed very carefully, due to the tendency of anaerobic soils to release large amounts of P to the overlying floodwater. This behavior has been studied and observed frequently in acid soils and has been attributed to the release of P from ferric oxides that are solubilized under reducing conditions. Recent studies in Manitoba have also measured large releases of P to overlying floodwaters in neutral to alkaline soils, for reasons that are not entirely clear (Amarawansha et al. 2015). In those studies, floodwater P increased by 2-15 fold in 10 of 12 soils, after the flooded soils became anaerobic. Therefore, the characteristics of the soil that the water is stored on and the duration of the storage period are important factors to consider.

CONCLUSIONS

The relatively dry, cold climate and nearly level topography of the Northern Great Plains results in relatively low rates of erosion; therefore, erosion control practices such as conservation tillage, perennial forages, cover crops and vegetated buffer strips do not appear to be very effective for reducing P losses in this region. However, water management practices that allow nutrient-rich snowmelt runoff water to be retained and used upstream in our watersheds show considerable promise for reducing P loss from farms in this region. Also, sound nutrient management practices are especially important in this region, given the challenges of intercepting dissolved P in snowmelt runoff.

Another issue that needs to be considered when evaluating any potential BMP for any region is that P loss is only one of many worthwhile objectives for improving agricultural sustainability and environmental protection. There are many benefits for conservation tillage, perennial forages, cover crops and vegetated buffers that deserve consideration as offsets for the increased risk of P loss.

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