THE UNIVERSITY OF MANITOBA

PHOSPHORUS LOSSES FROM SOIL AND VEGETATIVE RESIDUE UNDER SIMULATED FREEZING AND THAWING CONDITIONS

By

ABDELHAFID AHMED SALEH

The Thesis/Practicum Submitted to the Faculty of Graduate Studies in partial fulfillment of the

requirement of the degree

of

Master of Science

Department of Soil Science
University of Manitoba
Winnipeg, Manitoba. Canada

THE UNIVERSITY OF MANITOBA

FACULTY OF GRADUATE STUDIES

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ABSTRACT

The objectives of these studies were to quantify potential losses of vegetative P after wetting, freezing and thawing and to simulate the risk of P loss under snowmelt runoff condition in a cold climate.

Vegetative residues used in the first study were collected in fall of 2005 and 2006 from two pairs of fields in South Tobacco Creek watershed near Miami, Manitoba, Canada. One pair of fields consisted of a zero tillage field and a conventional tillage field. The other pair consisted of a perennial forage and an annually cropped field. In general, zero-till and perennial forage are traditionally used for reducing soil erosion and losses of particulate P with runoff. That is due to their benefit of maintaining residue on the soil surface, protecting the soil surface from dispersion and increasing infiltration. However, in this study, the analysis of the two years data of vegetative soluble reactive P (SRP) extracted from residue after exposure to wetting, freezing and thawing indicated that the potential risk of P loss to water from these residues is substantial. Therefore, in a cold climate such as in most of the Canadian prairies, zero-tillage and perennial forage may not reduce P losses compared to conventional tillage, unless the erosion risk and particulate P losses are high. The gently sloped landscape in this region produced uniform residue biomass across the cropped portions of each field resulting in no landscape effect on the P losses. The volume of water used for extraction also has an important influence on the concentration of SRP extracted. Water extractable SRP concentrations increased two fold when water volume were decreased by 50% indicating that low runoff volumes in a dry season could result in high concentrations of SRP in runoff.

A rainfall simulator study was used to measure the effect of soil test P, residue and freezing on SRP losses in runoff and percolate. Soil test P was the main factor influencing SRP losses with runoff in unfrozen soils. However, the effect of soil test P was reduced in frozen soils, probably because freezing reduced the effective depth of interaction between soil and runoff water. Adding residues increased SRP losses about three fold in the initial 15 minutes of runoff, indicating that the majority of residue P was easily extractable. Percolate losses and total losses of SRP (from runoff and percolate) were affected by a complex and inconsistent interaction between soil test P, residue and freezing.

Overall, the contribution of vegetative P to runoff P losses is significant, especially in early stages of runoff and is likely to be must important when soils are frozen and less interactive with surface runoff water and when runoff volumes are small.

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FOREWORD

The following thesis was prepared using the manuscript format outlined in "A Guide to Thesis Preparation for Graduate Student in The Department of Soil Science". Chapters were written in manuscript style, following format of the "Canadian Journal of Soil Science".

The nature of this M.Sc. thesis project is unique in that it was a marriage between research and extension activities. Field work was completed on a field-scale basis to allow producers the opportunity to see research at work and provide not only sound research and crop production information but to allow producers to witness ongoing research being conducted in a system which they employ on their own operations.

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1. Introduction

Phosphorus (P) is an important nutrient for growth of plants and often needs to be applied to agricultural land for optimal crop yield. It is required for many critical functions including photosynthesis, respiration, seed production and root growth. However, land application of supplemental P as animal manure, mineral fertilizer, and accumulation of vegetative residues can also increase the risk of P loss to surface water. The risk increases because P may accumulate at the soil surface as a result of its low solubility and mobility relative to other nutrients in soil. However, this accumulation of P at the soil surface has the potential to move with runoff into water bodies, causing eutrophication. That is because phosphorus is the most limited nutrient in many water bodies and a small agronomically insignificant loss of agricultural P can pose high risk of water quality degradation. Brookes et al. (1997) and the Canadian Council of Ministers of the Environment (2004) reported that phosphorus can cause eutrophication at concentrations as low as 0.02 to 0.035 mg L^{-1}; conversely, significantly higher concentration of P in soil creates little risk to crop production. Therefore, loss of phosphorus from agricultural land is considered to be an environmental problem more than an economic problem for farmers (Sharpley. 1994)

Generally, much attention has been paid to the effect rather than cause of these water quality problems. Furthermore, many of the historical efforts to reduce nutrient loading have been focused on point sources rather than non-point sources. However, recently phosphorus (P) input from non-point agriculture sources to surface water has received attention from water resource managers. Even though point source loading of P has been reduced as a result of their ease of identification and control, non-point agricultural sources are still providing adequate amount of P to maintain eutrophic conditions in receiving water bodies (Sharpley et al. 1994).

Assessment of P loss from non-point sources is difficult due to the diversity of uncontrolled pathways for these sources. Also, phosphorus delivery from land depends on complex interactions between source and transport factors which make the assessment more complicated. As a result, risk assessment tools such as the P index integrate soil test P with many agricultural management practices, as well as soil or field characteristics that influence potential P movement to surface waters. Sharpley et al. (2001) reported that non-point P loss from agricultural land depends on two main groups of factors: the critical source areas are where high P availability (source factors) overlap with high transport potential (transport factors).

Source Factors:

The major source factors that contribute to P loading from agricultural watersheds into water bodies include soil phosphorus and phosphorus from fertilizers, manures, and vegetation residues.

Soil Test Phosphorus Concentration (STP)

Even though agronomic soil test phosphorus (STP) values are not always accurate for environmental purposes, they provide a general idea about the risk of P losses from some areas, especially those which have received a high rate of P application. Sharpley et al. (1995) reported that long term application of fertilizer and/or manure at rates exceeding crop needs increases soil P concentration and the risk of phosphorus losses in runoff from agricultural systems.

As there is often a relationship between runoff P and soil test P, there is often a critical soil test P level for environmental purposes. Soil test P concentration that exceeds this critical point will cause unacceptable risk of poor water quality. Therefore, these critical thresholds are used to identify areas where any further accumulation of phosphorus either from manure, biosolids or commercial fertilizers should be prevented (Sharpley et al. 1995).

Application of Phosphorus Fertilizers

Phosphorus concentrations in soils of most agricultural land were initially very low and P fertilizers have been added to enhance crop yields. However, the addition of P fertilizers in excess of crop needs in some areas has increased soil P beyond what is necessary to optimize crop production. For example, Sharpley et al. (1994) compared the P concentration in soils used for vegetable production in Wisconsin in 1967 and the P concentration of the same soils in 1990; they found significant increases in the soil P concentrations during this period, from 34 to 48 mg kg^{-1}, respectively. Those changes were attributed to long term application of synthetic P fertilizers.

Application Time and Rate of Phosphorus Fertilizer

An increase of the P application rate often increases risk of P loss independently of the STP level (HuanChao et al. 2004). Schroeder et al. (2004) suggested that timing of manure and mineral fertilizer application relative to runoff events plays a key role in the magnitude of observed P losses. For example, the risk of recently applied P loss is high when the application is made in periods of high probability of intense rainfall, to water-saturated or snow-covered soil, to sloping ground, and to flood-prone areas. Water passing over the soil surface interacting with recently applied manure or fertilizer P is likely to have a high concentration of P, much of it as dissolved P. For example, Edwards and Daniel (1994) found that concentration of P in runoff from two soils that received poultry litter and inorganic fertilizers was highest in the first runoff after application of those P sources.

Manures and Biosolids

The behavior of manures and biosolids P after application to soils is different from that of soluble P fertilizers. Manures and biosolids contain lower concentrations of water soluble phosphorus and also wide ranges of organic P concentration and a variety of other elements and materials which may affect P chemistry.

Increasing animal production in certain areas is increasing the amounts of manure being applied to the land which often causes P surpluses on farms and in the surrounding watershed (Sharpley et al. 2001). The reason for these imbalances is that manure and biosolids are often applied at a rate or frequency that exceeds the P needs of crops. These sources have relatively low N:P ratios, compared to crop removal. Therefore, applying manures and biosolids on the basis of N requirement by crops often results in accumulation of excess P in soils. Accumulation of P in excess of crop needs increases the potential for runoff losses.

Vegetative Phosphorus

The extent to which vegetation residues contribute to total P losses from agricultural land depends on their decomposition and mineralization rate and also on the concentration of P in their tissues. Furthermore, there are other factors that could affect the amount of P release from vegetative residues. These factors include soil microbial activity, agricultural management practices (e.g., zero-till or conventional till) and weather conditions. Zero-tillage effectively reduces total P (TP) loss, relative to conventional tillage by reducing erosion of particulate P (PP) during summer and early spring, but the remaining dissolved P (DP) load is composed mainly of leached soluble compounds which increase during snowmelt (Hansen et al. 2000). Also Romkens et al. (1973) found higher concentrations of DP in surface runoff from no-till fields than in runoff from conventional-till fields. The increased runoff of DP from no-till soils may be derived largely from the greater amounts of crop residues on the soil surface. If delivered to surface water bodies, such soluble P compounds can be immediately bioavailable to aquatic producers and decomposers.

Cold weather could reduce decomposition and mineralization rates by impeding microbial activity. In contrast, freezing and thawing increase the P losses, mainly as DP, by disrupting crop tissues, leading to more P release. For example, Roberson et al. (2007) reported that freezing, freeze–thaw and drying treatments provided significantly greater water SRP from alfalfa compared to that from fresh alfalfa. Bechmann et al. (2005) reported similar results for annual ryegrass. Therefore, the potential risk of P loss from vegetative residues is expected to be high in cold climates because such freezing and thawing of plant tissue occurs during spring snowmelt when much of the runoff occurs.

Transport Factors

Transport factors are considered to complement the source factors and are responsible for moving P from terrestrial sources to water bodies.

Generally, the three pathways of phosphorus movement to water bodies include leaching of DP and PP, erosion of PP, and runoff of DP. Leaching of DP is generally higher in coarse textured soils compared to soils with fine texture, except for cracking clay soils with preferential pathways. However, P loss by erosion and runoff (PP and DP) increases in fine textured soils due to low infiltration rates.

In addition to texture, there are other factors that could increase P loss by erosion and runoff. These include weather factors such as precipitation amounts (rainfall and snowfall), intensities and duration. Snow usually melts gradually; therefore, snowmelt runoff usually has lower kinetic energy than rainfall runoff. The consequence of that is limitation of the PP loss which occurs by the erosion pathway (Hansen et al. 2000). In contrast, losses of DP by snowmelt runoff is more common due to rupturing of plant cells by freezing and thawing leading to more DP releases (Bechmann et al. 2005).

Landscape factors also affect the amount of P loss by runoff or erosion. Thus, in a steep slope the risk of PP loss is high, especially if the slope is near an open surface water. Conversely, in flat landscapes the losses of P are expected to be mostly as DP due to the slow water movement. Land and crop management practices also play an important role for decreasing or increasing P loss and the form of P loss as well. For example, intensive tillage systems increase the chance of P loss as PP; conversely, annual cover crops could increase the P loss as DP from field especially in cold areas where freezing and thawing increase the amount of P released from plant tissue (Bechmann et al. 2005).

In the Canadian prairies, the combination of a flat landscape with freezing and thawing conditions in the cold climate is favorable for losing P as DP (Glozier et al. 2006). This DP lost is more harmful to aquatic environments than PP due to its higher biological availability to cyanobacteria; DP is also more difficult to intercept, once it starts to move with and into water.

Research Objectives

The study of phosphorus is essential because phosphorus (P) is an important nutrient for growth of crops and aquatic vegetation and often needs to be applied to land for optimal crop growth. Land application of P as animal manure, biosolids (sewage sludge), and synthetic fertilizer can increase the risk of P loss to surface water (Miller et al. 1994). This risk occurs under a variety of climatic conditions. However, the risk appears to be very high during snowmelt in the Canadian prairies, when 80% of annual runoff occurs as result of reducing soil infiltration in frozen soil (Nicholaichuk 1967; Glozier et al. 2006), and also due to freezing and thawing which ruptures the cells of vegetative residues, leading to substantial risk of phosphorus release (Roberson et al. 2007). Most of Manitoba's agricultural landscapes are flat; therefore, the phosphorus losses from those soils by surface runoff are mainly as DP rather than PP. Under these circumstances of freezing and thawing during early spring snowmelt-dominant runoff and over flat landscapes, P losses from thawing vegetative residues may form a substantial proportion of total P losses from agricultural land, especially when land is zero-tilled or planted to perennial forage crops. Therefore, understanding the impacts of freezing and thawing on the losses of P from vegetative residues is the main objective in this study.

Overall objectives are: 1) to quantify potential losses of vegetative P after wetting, freezing and thawing; and 2) to simulate the risk of P loss under snowmelt runoff condition in a cold climate.

The specific objectives are to quantify potential losses of vegetative P as affected by: 1) cropping and tillage systems, 2) landscape positions, 3) residues:water ratio, 4) interactions between soil and vegetative P under frozen and unfrozen conditions.

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Chapter 2

EFFECT OF TILLAGE, CROPPING, AND LANDSCAPE POSITION ON RELEASE OF PHOSPHORUS FROM THAWING VEGETATIVE RESIDUES

2.1 Abstract

A two year study was conducted to investigate the effect of tillage, crop management and landscape position on the potential P losses from vegetative residues in the South Tobacco Creek watershed near Miami, Manitoba, Canada. Quadrats (0.25 m^2) of vegetative residues were collected from two pairs of fields in fall 2005 and 2006. One pair of fields consisted of a zero tillage field and a conventional tillage field. The other pair consisted of perennial forage and an annually cropped field. All vegetative residues were extracted under laboratory condition, after exposure to wetting, freezing and thawing. Soluble reactive P (SRP) in the water extracts was used as an indicator of risk of P loss. For the cropped portion of the field, yield of SRP (kg P ha^{-1}) in residues was 6 to 16 times greater from zero-tillage than from conventional tillage and it was also 39 to 51 times greater from perennial forage than from annual crops. Yield of SRP was highly correlated to the vegetative biomass collected in each quadrat. In all fields there were no significant differences in the SRP extracted from landscape positions (upper, mid, and lower slope) and also there were no significant field by landscape effect on the extractable vegetative P.

Doubling the ratio of water to residue diluted the concentration of SRP extracted by approximately 50%. Therefore, the seasonal fluctuation of snowmelt volume is likely to

play a significant role in the concentration of P lost from vegetative residues during spring runoff.

2.2 Introduction

Vegetative residues are considered as an important source of phosphorus loss from agriculture land, especially under freezing and thawing conditions in cold climates. Under field conditions, biological, chemical and physical decompositition are the major processes by which vegetative residue P is made available to subsequent crops or released to surface waters. However, the rate of decomposition and release of nutrients (including P) varies among crop residues depending on their chemical and biochemical characteristics, soil properties and on environmental conditions such as weather (Tian et al. 1992; Vanlauwe et al. 1997). Also, the amount of nutrients released from plant varies with plant parts. For example, Roberson et al. (2007) found that significantly greater amount of SRP was released from fresh leaves (4%) than from stems (1%) of alfalfa. The amount of P released from plant materials also increased when the plant tissue dried out. Bundy et al. (2001) found the amount of soluble phosphorus released from drying alfalfa tissue was higher than that released with freezing/ thawing alfalfa tissue.

Plant residues generally decompose more slowly under no till than under conventional-tillage management, resulting in slower release of nutrients from no-till residues (Lupwayi et al. 2007). However, this assumption is not always valid because, as mentioned, the amount of nutrient released from plant residues depends not only on the rate of biological decomposition (ease of decomposition), but also on the nutrient concentration in the original plant residues and the intensity of chemical and physical processes. For example, White (1973) suggested that leaching of ions from plant tissue is highly dependent on the ions' behavior in plant tissue, such as mobility and solubility, which is affected by plant age and the rate of decomposition of the dead plant material. Also, the ions' solubility in the leaching water has a significant impact on the leaching rate. Therefore, if conservation tillage affects any of these other factors (e.g. type of plant residues on the soil surface), the release of vegetative P to surface runoff could also be affected.

Generally, although cover crops and conservation tillage are considered as important management practices to reduce the phosphorus loss from agricultural land, especially particulate phosphorus (PP) by reducing soil erosion, they may pose an environmental risk by increasing the loss of soluble, bioavailable P (Sharpley et al. 1994). Romkens et al. (1973) also found higher concentrations of DP in surface water runoff from no-till fields than in runoff from conventional-till fields. In another study, Simard et al. (2000) suggested that the benefit of catch crops or grassland for controlling the transport of P is less clear and these practices may increase P losses because high concentrations of P would be released by plant tissues and be available for losses by runoff.

Bechmann et al. (2005) compared the phosphorus losses from manured and catch cropped soils under frozen and unfrozen conditions. They found that before freezing, the concentrations of TP in runoff from catch cropped soils were much lower than those from bare and manured soils. TP concentration in runoff from bare and manured soils were strongly correlated to concentration of suspended sediments (SS), which means soil erosion was the major mechanism of phosphorus loss from those soils. Concentration of dissolved reactive phosphorus (DRP) on the other hand was not different among unfrozen treatments. Freezing and thawing had a minor effect on the phosphorus losses from manured and bare soils; however, the concentration of DRP in runoff from catch cropped soils increased dramtically after freezing. Also, the concentration of SS increased significantly in the catch cropped soil after freezing, indicating that there was breakdown or loss of plant material in runoff which allowed more erosion of soil to occur. Therefore, after freezing, TP losses were much greater from soils with catch crops than those without.

The risk of P loss from vegetative residues is expected to be highest in cold climates because freezing and thawing disrupts plant tissues, leading to a release of vegetative P during spring snowmelt. Bundy et al. (2001) reported that freezing, freeze- thaw and drying treatments provided significantly higher water SRP extracted from alfalfa compared to that from fresh alfalfa. They also found SRP concentrations in alfalfa samples which were collected immediately after killing frosts in October were significantly higher than the SRP concentration in alfalfa samples that were sampled later in December from the same site. They suggested that the temporal differences could be due to tissue disruption resulting from low temperatures (below 0 °C) for 18 days between the period of 7 Oct. and 10 Dec. resulting in release and leaching of SRP from alfalfa during the period between sampling times.

Repeated freeze–thaw cycles are more effective than continuous freezing for increasing phosphorus loss from vegetative residues (Bechmann et al. 2005). Furthermore, variation in cellular structure may lead to differences among plant cells in their resistances to disruption by a single freezing–thawing cycle (Bechmann et al. 2005).

Many studies have reported that the dominant form of P released under freezing and thawing conditions is dissolved phosphorus (DP). For example, Wendt and Corey (1980) identified higher runoff concentrations of DP from fields covered with frozen crop residue such as alfalfa than from tilled fields. Borresen and Uhlen (1991) also found that freezing treatment increased the concentration of dissolved reactive P in runoff from ryegrass plots from 0.15 mg L^{-1} before freezing to 0.68 mg L^{-1} after freezing.

Little et al. (2007) studied the forms of P loss with runoff from eight sites in Alberta which included grassland and cultivated cropland. They reported that spring runoff during snowmelt accounted for 90% of total runoff volume during the three years of their study. They also found that the majority of the P loss from all sites was dissolved reactive phosphorus (DRP). In another study, Glozier et al. (2006) reported that the concentration of dissolved nutrients including DP were higher in the spring snowmelt runoff generated from snowmelt than from summer rainfall runoff near Miami, Manitoba. However, sediments and carbon were generally higher in summer runoff than in spring runoff. These variations reflect the difference in the kinetic energy between summer and spring runoff; spring runoff, created from snowmelt usually has lower kinetic energy compared to that of summer rainfall runoff. However, these variations are also affected by the consequences of snowmelt running over frozen soils covered by frozen and thawed vegetative residues.

2.3 Objective of the Study

The objectives of the study were to quantify potential losses of vegetative P as affected by: 1) cropping and tillage fields, 2) landscape positions, 3) residue:water ratio.

2.4 Material and Methods

2.4.1 The Area of Study

The area of our study was the South Tobacco Creek (STC) watershed, a small catchment of 76 km^2 located in the Red River Basin near Miami, Manitoba, approximately 150 km southwest of Winnipeg. Soil textures in this area are mainly clay-loams formed on moderately to strongly calcareous glacial till which overlays shale bedrock. Most of the land in this catchment is in annual cropping fields. Average annual precipitation is approximately 570 mm, and approximately 25% of the precipitation falls as snow (AAFC 2006)

Four fields were used in this experiment (F3, F4, F11, and F12). Two fields were established to investigate the benefits to surface water quality of converting land from conventionally-tilled annual crops to perennial forage (F3 and F4 respectively); the other two fields (F11, and F12) were established to compare zero tillage to conventional tillage, respectively. Vegetative residue samples were collected from four replicates of three landscape positions (upper, midslope, and lower slope) for each of the fields. In addition, residue samples were collected from the riparian areas in the annual crop and perennial forage fields (F3 and F4) for reference purposes, but the riparian samples were not included in the statistical analyses for field and landscape position effects.

Replication of the landscape positions were distributed randomly throughout the conventional tillage and zero tillage fields. However, replicates of annual crop and perennial forage residue samples were collected from four transects (North East, North West, South East, and South West) (Figures 2.1 and 2.2). Crop and tillage history for the two pairs of fields is summarized in Tables 2.1 and 2.2. The residues left on the soil surface varied from one field and year to another. In 2005, the residues left after seeding were 50% surface and 12 % standing in the zero-till field (F11), and 25% surface and 0 % standing in the conventional till (F12). In 2006, the after seeding residue survey showed the zero till field had 45% surface and 15 % standing barley residue and the conventional till field had 15% surface and 1-2% standing barley residue.

Table 2.1. Annual crop and perennial forage fields (F3 and F4) cropping and tillage history

Year	Field	Crop [z]		Seeded month	Seeded week	Harvested month	Harvested week	Spring Tillage [y] (1)	Spring Tillage (2)	Fall Tillage (1)	Fall Tillage (2)
2001	F3	AC	Flax	May	4	September	3	L.D. with H	H / P	H.D. with H	No tillage
	F4	AC	Flax	May	4	September	3	L.D. with H	H / P	H.D. with H	No tillage
2002	F3	AC	Wheat	May	1	July	4	L.D. with H	No tillage	H.D. with H	A. R.
	F4	AC	Wheat	May	1	July	4	L.D. with H	No tillage	H.D. with H	A. R.
2003	F3	AC	Canola	May	2	August	4	L.D. with H	H / P	H.D. with H	No tillage
	F4	AC	Canola	May	2	August	4	L.D. with H	H / P	H.D. with H	No tillage
2004	F3	AC	Oats	May	4	September	4	L.D. with H	No tillage	H.D. with H	No tillage
	F4	AC	Oats	May	3	September	4	L.D. with H	No tillage	H.D. with H	No tillage
2005	F3	AC	Flax	May	2	September	3	L.D. with H	No tillage	H.D. with H	H.D. with H
	F4	PF	Alfalfa	None	None	July	2	L.D. with H	No tillage	H.D. with H	No tillage
2006	F3	AC	Wheat	May	2	August	1	L.D. with H	No tillage	H.D. with H	No tillage
	F4	PF	Alfalfa	None	None	July	4	No tillage	No tillage	No tillage	No tillage

[z] AC = Annual crops; PF = Perennial forages

[y] L.D. with H = Light Duty Cultivator with harrows; H/ P = Harrows /Packers. A. R. = Anhydrous Rig (with knives). H.D. with H = heavy Duty Cultivator with harrows.

Table 2.2. Zero tillage and conventional tillage fields (F11 and F12) cropping and tillage history

Year	Field	Crop [z]		Seeded month	Seeded week	Harvested month	Harvested week	Spring Tillage [y] (1)	Spring Tillage (2)	Fall Tillage (1)	Fall Tillage (2)
2001	F11	ZT	Oats	May	3	September	3	No tillage	No tillage	H / P	No tillage
	F12	CT	Oats	May	4	September	3	L.D. with H	H/P	L.D. with H	No tillage
2002	F11	ZT	Flax	May	3	September	3	No tillage	No tillage	H / P	No tillage
	F12	CT	Flax	May	3	September	3	L.D. with H	H / P	H / P	H.D. with H
2003	F11	ZT	Wheat	May	2	August	3	No tillage	No tillage	No tillage	No tillage
	F12	CT	Wheat	May	2	August	3	L.D. with H	None	H.D. with H	None
2004	F11	ZT	Canola	June	1	October	1	No tillage	No tillage	None	No tillage
	F12	CT	Canola	June	1	October	1	L.D. with H	None	H.D. with H	None
2005	F11	ZT	Barley	May	1	August	3	A. R	No tillage	H/P	No tillage
	F12	CT	Barley	May	1	August	4	L.D. with H	A. R.	H.D. with H	None
2006	F11	ZT	Canola	May	3	August	3	A. R	No tillage	None	No tillage
	F12	CT	Canola	May	3	August	3	L.D. with H	A. R.	H.D. with H	None

[z] ZT = Zero-till; CT = Conventional tillage

[y] L.D. with H = Light Duty Cultivator with harrows; H/ P = Harrows /Packers. A. R. = Anhydrous Rig (with knives). H.D. with H = heavy Duty Cultivator with harrows.

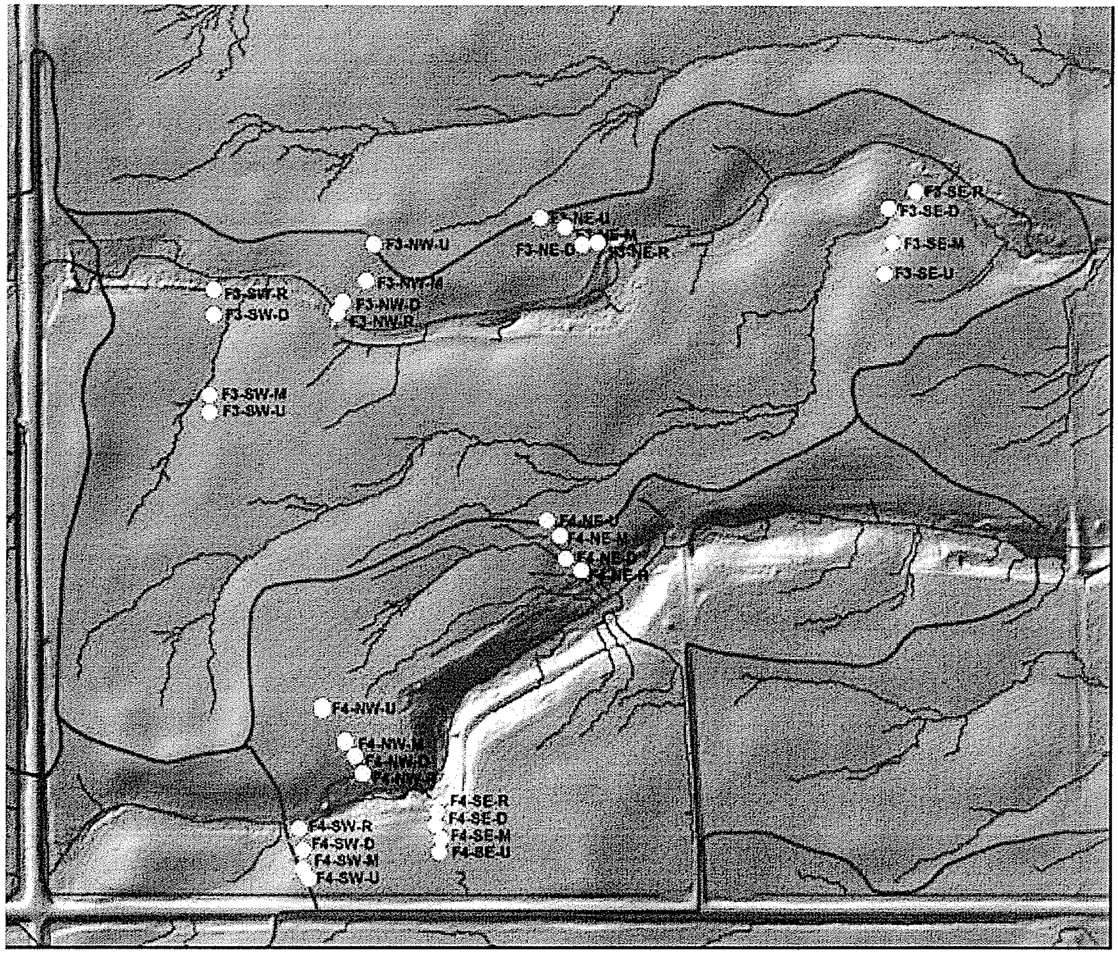

Figure 2.1. Annual crop and perennial forage fields (F3 and F4) sampling locations.

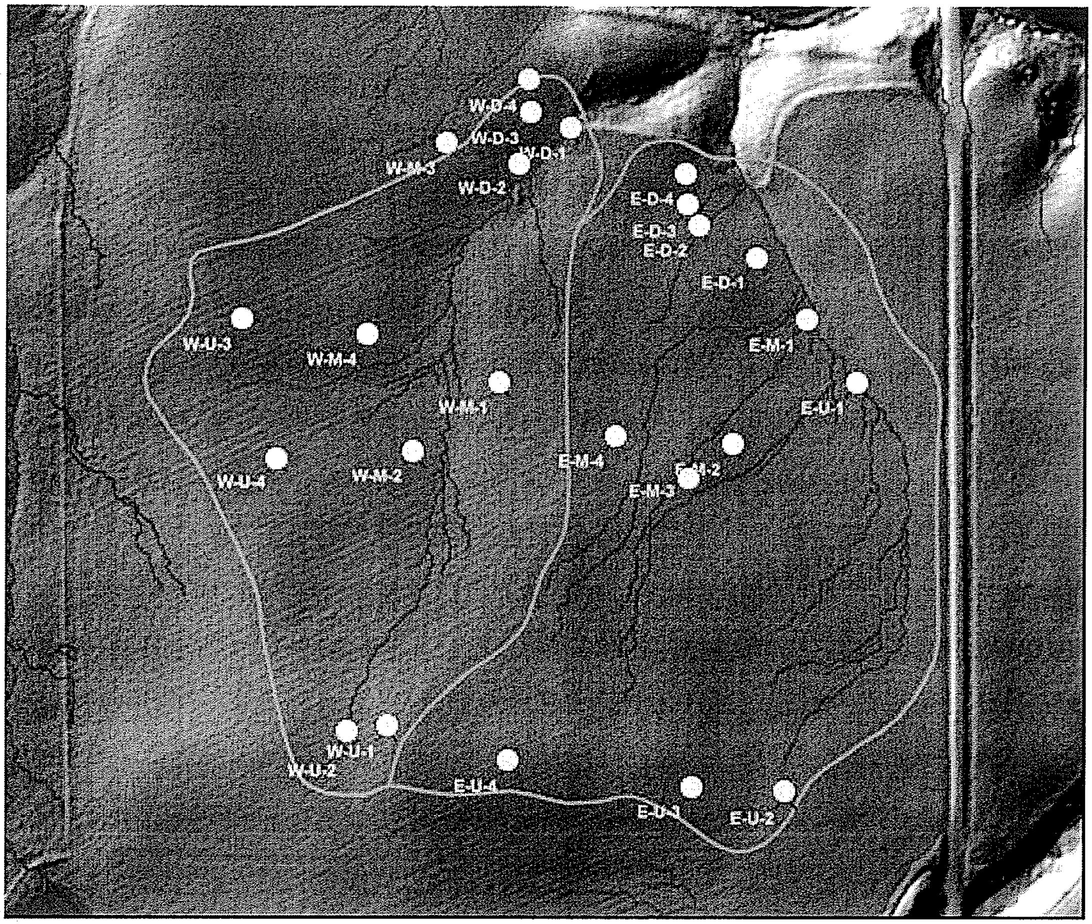

Figure 2.1. Zero tillage and conventional tillage fields (F11 and F12) sampling locations.

2.4.2 Residue Sampling and Extraction

Vegetative residues were collected in late October 2005 and 2006 (Oct. 25, 2005 and Oct. 24, 2006). Two quadrats (0.25 m^2) of vegetative residue samples were collected from each landscape position on each field. Both subsamples were collected within two metres of where soil fertility samples had been taken. The two subsamples from each location were combined to form a composite sample and stored in a freezer prior to further processing. A small sample was taken for determining the moisture content by drying for 48 h at 65°C. The moisture content was used to calculate the vegetative residue and nutrient extracted on a dry matter basis, in addition to the area basis.

For the water extraction, one quarter of the composite sample was weighed into polyethylene bags and 3.7 L of deionized water was added to each bag (on an area basis, this is equivalent to 3 cm of runoff or a snow depth of approximately 30 cm). For 2006, 10 randomly selected samples from cropped positions in all fields were also extracted using the equivalent of 1.5 cm of runoff to investigate the effect of water:residue ratio on the concentration of P, N and C extracted from the residue in that year. For all extractions, the bags were secured by plastic cable ties, then rolled and mixed to ensure all residue was in contact with water. Samples were soaked for 24 hrs at room temperature and then frozen for at least 24 hrs at -15°C. Samples were then thawed for 36 hrs and gently mixed by rolling the bags. The contents of the bags were poured into household plastic colanders that were placed in plastic pails; the colanders had openings of approximately 5 mm and were used to separate most of the residues from the aqueous extracts. Samples were allowed to drain in the colander for 1 min before removing the colanders and allowing the extracts to settle for another 5 min. A 500 mL subsample of extract was then gently decanted into a storage bottle for analyses.

2.4.3 Filtration and Analyses of Extracts

Soluble reactive phosphorus (SRP) was analysed by using the ascorbic acid-molybdate blue method (Murphy and Riley 1962) after filtering to 0.45 μm.

2.4.4 Statistical Analyses

Statistical analysis of variances was performed using Statistical Analysis Systems software (SAS) package (SAS 9.1). A two way factorial design was used to test the degree of the significance of the field effect, landscape position effect and the interaction between fields and landscape positions. Fisher's (protected) least significant differences (LSD) test was used to compare the fields and landscape position treatment means. Least square linear regression analysis (PROC REG) was used to describe relationships between the SRP extracted by using two volumes of water (1.85 and 3.75 L). Microsoft Excel was used to determine correlation between extractable SRP and vegetative residue mass.

2.5 Results and Discussion

2.5.1 Tillage Effect on Risk of SRP Loss

The concentrations of SRP extracted from the residue of the ZT field were significantly greater than from the CT field (Table 2.3). The same trend was observed in yield of extractable P expressed on the area basis (kg P ha^{-1}) because all samples were taken from an equivalent area and extracted with a similar volume of water. The average concentrations of SRP in extracts from the zero tillage field were 8.2 and 16.3 mg P L^{-1} in 2005 and 2006 respectively, approximately 400 and 800 times greater than the eutrophication threshold adopted by the Canadian Council of Ministers of the Environment (CCME 2004).

Generally, concentration of SRP extracted from each tillage field reflected the mass of surface vegetative residues, both of which were much greater in the ZT field than in the CT field in both years (Table 2.3). However, relationships between the biomass weight and the extracted SRP were not similar between fields. In both years, this correlation was significant for CT fields only (Figures 2.3, 2.4, 2.5 and 2.6). The reasons for the poor correlations between biomass and extractable SRP in the ZT field are not known. However, part of the variability in effect of biomass on SRP extracted from ZT field may be due to greater variability in types of biomass collected from this field, where fresh vegetation was more frequently included in the residue samples.

Table 2.3. Effect of field and landscape position on the soluble reactive P (SRP) extractable from vegetative residues in zero-till (ZT) and conventional tillage (CT) fields

	Treatment		Sampling date Oct. 25, 2005				Sampling date Oct. 24, 2006			
	Field	Landscape Position	SRP		Residue biomass	SRP yield per kg biomass[z]	SRP		Residue biomass	SRP yield per kg biomass[z]
			mg L^{-1}	kg ha^{-1}	(T ha^{-1})	(mg kg^{-1})	mg L^{-1}	kg ha^{-1}	(T ha^{-1})	(mg kg^{-1})
Field means	ZT		8.2 *a*[y]	2.4 a	6.9 a	359	16.3 a	4.9 a	6.4 a	854 a
	CT		1.5 *b*	0.4 b	2.1 b	195	0.9 b	0.3 b	1.6 b	159 b
Landscape means		Upper	5.6	1.6	5.3	271	8.9	2.6	3.8	569
		Mid	5.2	1.5	4.7	257	9.7	2.9	4.0	547
		Lower	3.7	1.1	3.5	304	7.7	2.2	4.2	403
Field X Landscape means	ZT	Upper	8.9	2.6	7.4	377	16	4.8	5.6	859
		Mid	9.7	2.9	7.7	355	19	5.7	6.5	1033
		Lower	6.1	1.8	5.5	346	13	4.1	7.0	670
	CT	Upper	2.3	0.7	3.2	164	1.9	0.5	2.1	279
		Mid	0.8	0.2	1.6	160	0.3	0.08	1.4	60
		Lower	1.3	0.4	1.6	262	0.6	0.3	1.4	137
ANOVA		df	Pr> F	Pr> F	Pr> F	P>F	P>F	P>F	P>F	
Field		1	0.0005	0.0005	<0.0001	0.091	<0.0001	<0.0001	<0.0001	<0.0001
Landscape		2	0.59	0.59	0.123	0.59	0.447	0.5	0.88	0.53
Field* Landscape		2	0.57	0.57	0.364	0.78	0.324	0.276	0.41	0.33
CV (%)			79	79	36	60	45	45	39	63

[z] Since the same volume of water was used for all extractions (equivalent to 3 cm of runoff) and residue biomass varied across treatments, the ratio of water to residue was variable among treatments and replicates.

[y] Mean values followed by the same letter within a column for a group of means are not significantly different ($P < 0.05$).

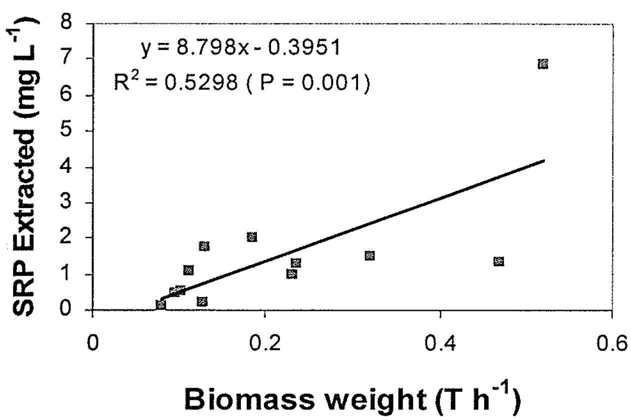

Fig. 2.3. The correlation between SRP losses and residue biomass weight in the CT field (2005)

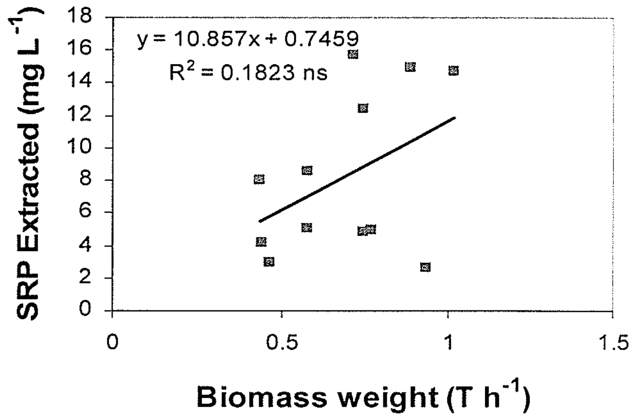

Fig. 2.4. The correlation between SRP losses and residue biomass weight in the ZT field (2005)

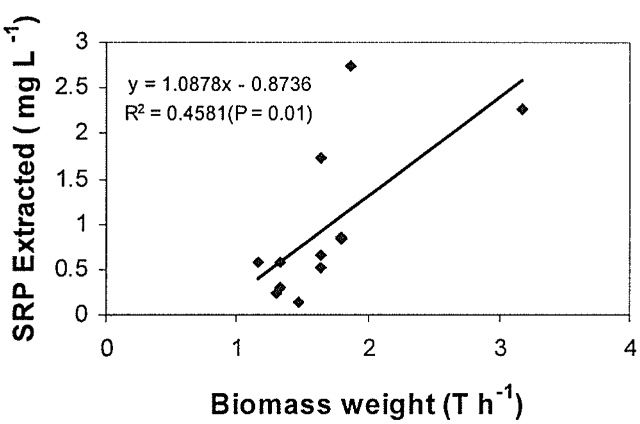

Fig. 2.5. The correlation between SRP losses and residue biomass weight in the CT field (2006)

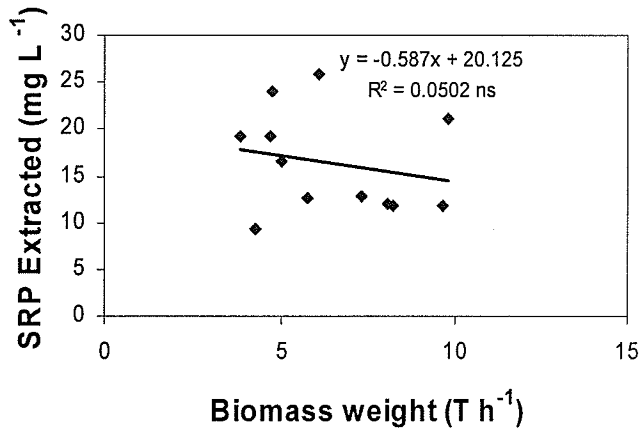

Fig. 2.6. The correlation between SRP losses and residue biomass weight in the ZT field (2006)

The SRP yield per kg biomass (mg P kg^{-1}) was not significantly different between the two tillage fields in 2005. Therefore, in 2005 the difference in weight of residue biomass for the two fields was the main factor that accounted for the high release of SRP from ZT. However, yield per kg of residue was significantly greater in the ZT field compared to CT in the fall of 2006. Therefore, in the second year the residue biomass weight and SRP yield per kg biomass combined together for a much greater release of SRP from ZT than from CT residues.

Differences in residue quantity for the two tillage fields are readily accounted for by the burial of residues in the conventional tillage field. Differences in SRP yield per kg of residue, however, may be due to differences in residue decomposition rates. In the conventional tillage field the majority of the vegetation residues could be decomposed relatively quickly in the short time due to the mixing of residues with the soil. Also, contact between soil and residue in the CT field may have reduced extractable P by increasing sorption of vegetative P by the soil. Some of these formerly buried residues (e. g. roots) could have been brought to the surface by tillage. Also, the residue from the CT field may have lost P due to sorption by small quantities of adhering soil during the laboratory extraction process. Therefore, the accelerated decomposition and sorption of vegetative P in the conventional tillage field may have reduced the yield of SRP per kg of residue remaining on the surface of the soil, compared to the zero tillage field.

2.5.2 Crop Effect on Risk of SRP Loss

In the two years 2005 and 2006, the results showed that the overall average concentrations and yields of extractable SRP for the perennial forage (PF) field was greater than for the annual crop field (AC). The average concentrations of SRP in extracts from the perennial forage field were 19.6 and 10.3 mg P L^{-1} in 2005 and 2006 respectively, approximately 500 to 1000 times the Canadian threshold for eutrophication (CCME 2004).

In both years, the residue biomass weight and SRP yield per kg biomass were significantly greater in the PF field compared to AC. Therefore, these two factors combined together for a much greater release of SRP from PF than from CT residues (Table 2.4). Generally, the large biomass weight per hectare in the PF fields was a substantial factor responsible for the greater concentrations and yields of SRP from these fields compared to the SRP extracted from AC fields. The greater SRP yield per kg biomass in the PF field is probably due mostly to its green, actively growing plants compared to the dead and partially decomposed residues in the AC field. In addition, the soil and crop residue contact in the AC field could have reduced the extractable P in residues through soil sorption reactions prior to sampling, especially if those residues were brought to the surface during tillage. Also, small quantities of soil attached to the AC field's residue may have sorbed residue P during storage and laboratory extraction.

The extractability of vegetative P under freezing and thawing conditions was probably greater than if the extraction had been done without the freezing and thawing cycle, due to the rupturing of plant cells by freezing and thawing. For example, Bechmann et al. (2005) found the quantity of water extractable P (WEP) from plant material increased from 0.9% to 40% of the TP before and after freezing and thawing, respectively.

Relationships between the biomass weight and the extracted SRP also were not similar between fields, as was the case for the zero-tillage and conventional tillage pair of fields. In both cropping years, this correlation was significant for PF fields only but not for the AC field (Figures 2.7, 2.8, 2.9 and 2.10). However, the lack of significant correlation between biomass and extracted SRP for the AC field contradicts the observations for the zero-tillage and conventional tillage pair of fields, where extracted SRP was significantly correlated with biomass in the conventionally tilled field, only.

Table 2.4. Effect of field and landscape position on the soluble reactive P (SRP) extractable from crop residues in perennial forage (PF) and annual crop (AC) fields

	Treatment		Sampling date Oct. 25, 2005				Sampling date Oct. 24, 2006			
	Field	Landscape Position	SRP		Residue biomass	SRP yield per kg biomass[z]	SRP		Residue biomass	SRP yield per kg biomass[z]
			mg L^{-1}	kg ha^{-1}	(T ha^{-1})	(mg kg^{-1})	mg L^{-1}	kg ha^{-1}	(T ha^{-1})	(mg kg^{-1})
Field means	PF		19.6 a[y]	5.9 a	4.5 a	1347 a	10.3 a	3.1 a	4.6 a	648 a
	AC		0.5 b	0.2 b	0.67 b	241 b	0.2 b	0.1 b	1.09 b	42 b
Landscape means		Upper	12	3.6	2.4	988	5.3	1.5	2.8	338
		Mid	10	3.0	2.8	679	5.6	1.6	2.9	349
		Lower	8	2.4	2.5	716	4.7	1.4	2.7	348
Field X Landscape means	PF	Upper	23	7.0	4.2	1688	10.5	3.1	4.6	644
		Mid	19	5.9	4.9	1209	11.1	3.3	5.0	655
		Lower	15	4.7	4.4	1146	9.3	2.7	4.29	645
	AC	Upper	0.5	0.2	0.6	289	0.1	0.03	1.1	31.8
		Mid	0.3	0.1	0.7	149	0.1	0.04	0.9	44.4
		Lower	0.6	0.2	0.6	287	0.2	0.07	1.1	51.8
Riparian areas[x]	PF	Riparian	20	6.0	6.5	939	18.8	5.6	9.2	668
	AC	Riparian	25.2	7.5	8.4	978	11.5	3.4	5.4	648
ANOVA		df	P>F	P>F	P>F	P>F	P>F	P>F	P>F	P>F
Field		1	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Landscape		2	0.4	0.4	0.8	0.4	0.8	0.8	0.8	0.9
Field* Landscape		2	0.4	0.4	0.9	0.6	0.8	0.8	0.5	0.9
CV (%)			53	53	49	43	63	63	28	34

[z] Since the same volume of water was used for all extractions (equivalent to 3 cm of runoff) and residue biomass varied across treatments, the ratio of water to residue was variable among treatments and replicates.

[y] Mean values followed by the same letter within a column for a group of means are not significantly different (P< 0.05).

[x] Riparian area values are presented for reference purposes only and are not included in the statistical analyses.

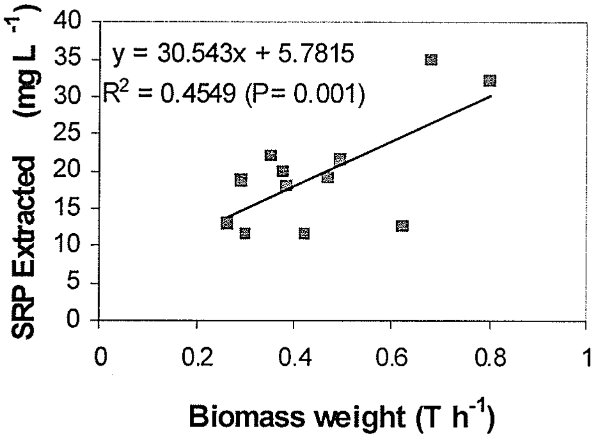

Fig. 2.7. The correlation between SRP losses and biomass weight in the PF field (2005)

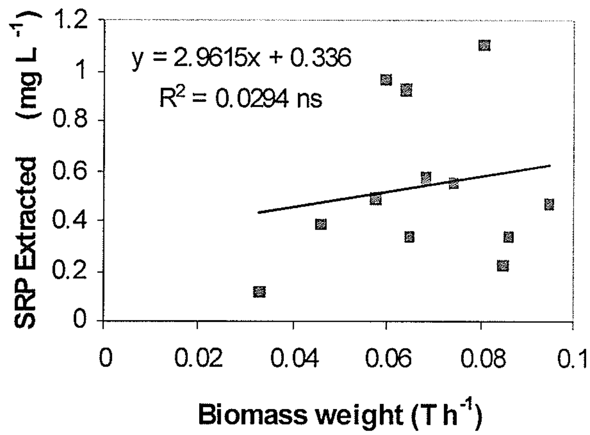

Fig. 2.8. The correlation between SRP losses and biomass weight in the AC field (2005)

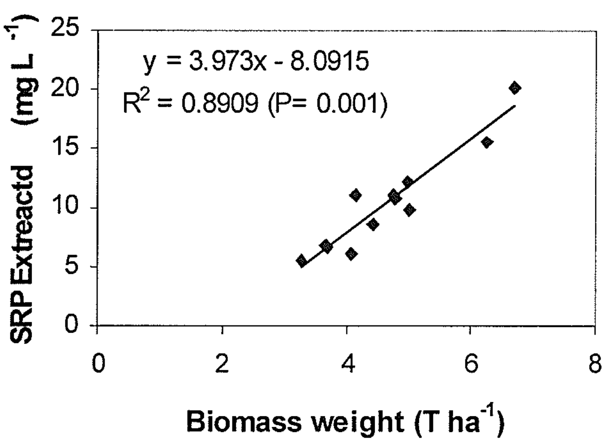

Fig. 2.9. The correlation between SRP losses and biomass weight in the PF field (2006)

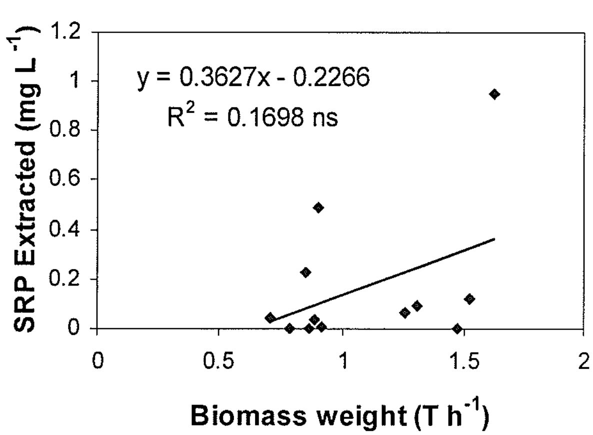

Fig. 2.10. The correlation between SRP losses and biomass weight in the AC field (2006)

In all fields, landscape position did not affect the concentration of SRP extracted from vegetative residues and also did not affect the yield of P expressed on an area basis in either field or either years (Table 2.3 and 2.4). Also, there was no significant field by landscape position interaction. These results parallel those for the mass of vegetative residues, which was also relatively uniform among the landscape positions.

For reference purposes, vegetative residues were also collected from riparian areas adjacent to the PF and AC fields. The mass of residues, concentrations and yields of SRP from the riparian areas in both fields were at least as great as those from the cropped portion of the PF field, indicating that riparian vegetation could contribute significant amounts of P to runoff during snowmelt.

The reasons for differences in extractable SRP between years for the same field were likely due to differences in weather conditions during those years. For example, the effect of rainfall intensity and freezing and thawing on vegetative P losses prior to sampling could have been different for each of the two years. As noted by Bundy et al. (2001) these factors may account for substantial losses of P from residues during the late fall period. Also, for the annually cropped field, the crop species were not similar from one year to the next.

2.5.3 Effect of runoff volume on the SRP losses

Extracted SRP concentrations were highly correlated for the two water volumes $R^2 =$ 0.97). The concentrations of the SRP extracted in 1.85 L water (equivalent to 1.5 cm of runoff) was approximately two times higher than those extracted by using 3.7 L water (Figure 2.5). The consistent doubling of P concentration with half the volume of water indicates that the extractable P in the residues is very soluble. These results also indicate that fluctuation in runoff volumes is an important factor that could affect the degree of water contamination with vegetative P during snowmelt. Low runoff volume due to dry weather or climate is likely to result in high concentrations of vegetative P in snowmelt runoff water.

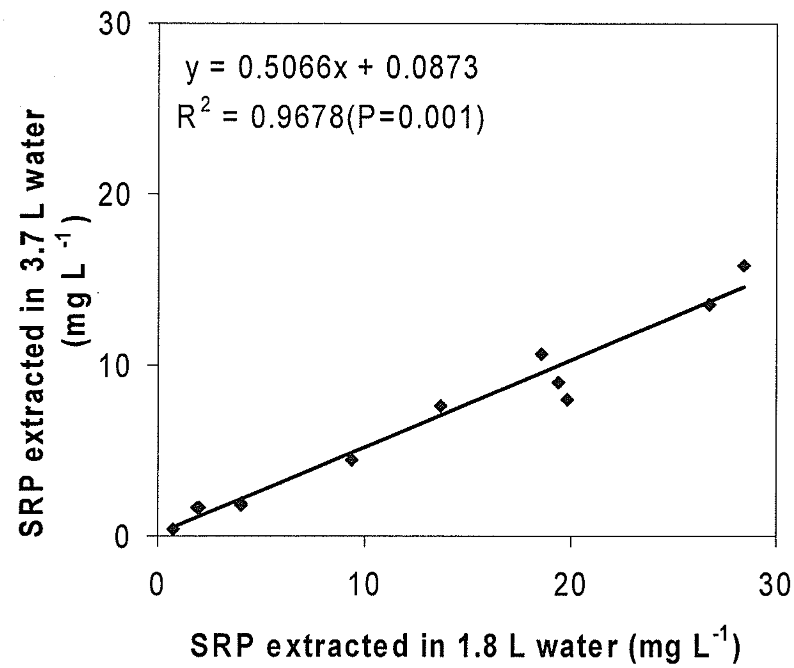

Figure 2.11. Relationship of different volumes of water with SRP extracted from a random selection of vegetative residues collected in October 2006.

2.6 Summary and Conclusions

Zero-tillage and perennial forages are generally considered to be a beneficial management practices to reduce soil erosion and the losses of PP due to retention of vegetative residues on the soil surface. However, this study showed that after exposure to wetting, freezing and thawing, the potential losses of SRP from these residues is significantly greater than those in conventionally tilled fields. Therefore, in a cold climate, zero-tillage and perennial forage may not reduce P losses compared to conventionally tilled annual crops, unless the erosion risk is large. The risk of a large proportion of P loss coming from vegetative residues is potentially higher in a region such as the Canadian prairies, where snowmelt over frozen soil and thawed residues accounts for the majority of runoff during the year and where the risk of water erosion is relatively low, due to a dry climate and nearly level landscapes.

Residue biomass on the soil surface is a key factor controlling the amount of extracted vegetative P. Zero-tillage and perennial forages generally result in higher biomass on the surface of soils compared to conventionally tilled annual cropping fields. In a cold climate, freezing and thawing may enhance the risk of P loss from this biomass. Vegetative residues were uniform among all landscape positions in all cropping and tillage fields resulting in no landscape position effect on the extractable SRP concentration and P yield per ha in these fields. In addition, vegetative residues in uncultivated soils (e.g. ZT and PF) appear to yield more water extractable P per kg of biomass than residues in cultivated systems (e.g. CT and AC). Therefore, the combination of higher mass of residues and higher P yield per kg of residue in uncultivated systems creates a substantial source of water soluble P that could be lost in runoff.

Runoff volume is also an important factor which affects the concentration of P lost from crops and vegetative residues. In our experiment reducing the extraction water volume by 50% resulted in a doubling of SRP concentrations. Therefore, low runoff volume could result in high concentrations of SRP in runoff. Low runoff volumes and high SRP concentrations are likely to occur in the Canadian Prairies and this relationship may partially explain the high frequency of eutrophic surface waters in this region.

Our results indicate that the amount of vegetative P extracted under laboratory conditions, after exposure to wetting, freezing and thawing events is highly correlated to the biomass weight that was present on the soil surface for the different tillage and cropping fields. However, this factor, alone, is not sufficient for assessing site vulnerability to P losses. For example, our measurements did not account for the benefit of these residues for reducing erosion and losses of PP. Also, the interaction between vegetative P and soil was not accounted for in this study; perhaps a shallow layer of thawed soil may be sufficient to sorb the vegetative P released during snowmelt runoff, especially in dry areas where small runoff volumes may allow significant interaction between soil and water.

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Chapter 3

EFFECTS OF SOIL TEST P, CROP RESIDUES, AND FREEZING-THAWING ON PHOSPHORUS LOSSES IN SIMULATED RUNOFF

3.1 Abstract

A rainfall simulation study was conducted to investigate the effect of soil test P, crop residue, and freezing-thawing on the phosphorus losses to runoff and percolate. In this study, soil test P was the dominant factor that controlled the amount of soluble reactive phosphorus (SRP) losses. The soil with very high soil test P generally produced approximately 10 times higher SRP concentrations in runoff than soil with medium to high soil test P. However, during the initial stage of runoff, this effect was significant only for unfrozen soils, probably due to limited effective depth of interaction between runoff water and frozen soils. Addition of vegetative residues caused approximately three times increases in SRP losses during the initial stages of runoff but did not affect SRP losses during the overall runoff period. There was no significant effect of freezing on SRP lost from the system except for the freezing by soil interaction previously mentioned. Since freezing did not influence the effect of residues on runoff SRP losses but freezing reduced the effect of soil test P, the proportion of SRP in runoff that originated from vegetative residues was likely greater in runoff from frozen soils than from unfrozen soils.

Over the entire simulation period (0-60 min) runoff water volumes were approximately 2 times higher than percolate volumes. None of the treatment factors, including freezing, significantly affected percolate volumes. Treatment effects, including freezing, on runoff volume were small and inconsistent. Therefore, significant volumes of water must have percolated through or around the frozen soils in the runoff trays. Effects of soil test P, residue and freezing on percolate losses of SRP and total export of percolate and runoff SRP were not consistent and were influenced by a complex interaction between all three treatment factors. Overall, in the majority of cases soil test P was the predominant factor controlling P export with higher losses from soil with higher P.

3.2 Introduction

Soil and vegetative residues are potential sources of P that can be lost during runoff. The amount of P released from each source could differ depending on the vegetation type, soil test P concentration (STP) and environmental conditions. The problem of soluble P losses, in particular, from vegetative residues is likely greatest from fields with no-till practices and high STP, especially in cold climates, where snowmelt runoff interacts with those residues after freezing and thawing, potentially increasing the extractability of P from both sources.

The accumulation of phosphorus in surface soil is a function of the characteristics of the P sources added (e.g. solubility), soil properties and agricultural management practices. Most soils have a high capacity for retaining the phosphorus applied as synthetic fertilizers or manure (Brookes et al. 1977). Soluble P forms such as these react quickly with the soil constituents and P adsorbs to fine mineral particles (clay, iron and aluminum oxides, carbonates, etc.), precipitates as inorganic compounds of low solubility (for example, as calcium and/or iron phosphates), or is retained in complex organic molecules. Thus, in most situations there is little movement of P through the soil profile, leading to the accumulation of P near the soil surface when it is applied at rates that exceed crop removal (Simard 2000). These accumulations of P increase the risk of P loss in runoff and, therefore, soil test P is an important factor for quantifying this risk (Sharpley 1977; Pote et al. 1996; Sawka et al. 2007).

In cold climates, the risk of phosphorus loss from agricultural land increases due to a rupture in the cells of vegetative residues caused by freezing and thawing cycles during the late winter and snowmelt events (Bechmann et al. 2005; Roberson et al. 2007) . In addition, the capacity of the soil to intercept vegetative P losses may be limited due to reduced infiltration in frozen soils. However, especially in situations where soil test P is low, the thawing surface soils may still have sufficient P sorption capacity to retain P, intercepting vegetative P before it reaches a significant waterway. Therefore, although we have traditionally focused on the benefits of vegetative residues to intercept nutrients lost from soil, perhaps we need to consider the opposite, the benefits of soil to intercept nutrients lost from vegetation.

3.3 Objectives of the Study

The main objectives of this study are (1) to investigate the interaction between crop residues and soil test P on P runoff losses under repeatable, controlled conditions (2) to evaluate the effects of freezing & thawing treatments on these interactions.

3.4 Materials and Methods

3.4.1 Treatments

Simulated rainfall was conducted with two soils, in a frozen and unfrozen state, with and without crop residues, in a factorial design, creating a total of eight treatments. Each treatment was replicated four times.

The Pembina clay loam and loam soils used in this experiment were collected on Oct. 24, 2006 from field F3 at the Steppler farm near Miami, MB. The soil properties are reported in Table 3.1. The two soils included a loam soil with medium to high soil test P concentration (MHP, 16 mg kg^{-1} Olsen extracted P) from an upper landscape position and a clay loam soil with very high soil test P (VHP, 49 mg kg^{-1} Olsen extracted P) from a low landscape position.

Spring wheat straw (*T. aestivum*) was used as the vegetative residue added to the surface of the soils. These residues were moistened with a small amount of water prior to placing the residue on the soil surface, taking care to prevent nutrient leaching out of residues. Residue treatments were applied at a rate of 10526 kg ha^{-1}; this rate was equivalent to the arithmetic mean (not geometric mean) residue biomass on the surface of the ZT and PF fields in the first experiment discussed in chapter 2.

For the purpose of determining the effect of freezing and thawing on the water extractable P from residue alone (Table 3.2), two pairs of wheat straw samples (300 g each) were extracted by using 3.7 L of deionized water. One pair of straw samples was moistened for 24 h, frozen, thawed and extracted according to the methods described in Chapter 2 (section 2.4.2). However, in this extraction a second pair of samples was not exposed to freezing and thawing treatment so that the potential of nutrient solubilization in unfrozen residues could also be measured.

Soil was sieved twice through 10 mm mesh to ensure that soil aggregates were reasonably uniform in size. Soil was placed in the runoff boxes in several layers, placing each layer before adding another. After the soil boxes were filled to a depth of 5 cm and packed to a bulk density of 1 g cm^{-3}, the soil surface was leveled by using a flat plexi-glass plate.

Table 3.1 Soil properties and nutrient analysis for the runoff experiment

	pH	S.O.M. %	CEC mmol kg^{-1}	Soluble Salts dS m^{-1}	Olsen P	Exchangeable Mg	Ca	Na	Soil texture Sand	Silt	Clay
					mg kg^{-1}				%		
Very High soil P (VHP)	6.9	4.8	253	0.8	49	637	3698	12	39	32	29
Medium-High soil P (MHP)	7.6	2.8	302	0.8	16	462	5129	12	43	30	27

Table 3.2 Water extractable soluble reactive P (SRP) in wheat straw added as surface residue

	SRP (mg L^{-1})	SRP yield per kg biomass (mg kg^{-1})	Equivalent SRP yield per hectare [x] (kg ha^{-1})
+F Residue [z]	2.3	15	0.153
-F Residue [y]	1.9	12	0.126

[z] +F Residue = SRP extracted from residue after exposure to wetting, freezing and thawing.
[y] -F Residue = SRP extracted from residue after exposure to wetting, without freezing and thawing.
[x] Potentially soluble P extracted from residues applied to the soil trays at a rate of 10526 kg residue ha^{-1}.

The initial level of the soil surface was 10 mm below the edges of the frames. During prewetting, soil boxes were placed on a level platform and water was supplied through the lower compartment in each soil box by using connection tube which delivers water from a small tank via gravity. Water level in the tank was controlled at 10 mm above soil level by using a float valve. Before rainfall simulation was initiated, water was drained by gravity from the boxes for several minutes.

The freezing treatment consisted of storing prewetted soil (with or without residues) in chest freezers at -15°C for 4 days. After 4 days, runoff boxes were taken out of the freezers for thawing. Digital thermometers were used to monitoring the changes of soil temperatures during the freezing period and to determine the time when soil temperature reached the desirable point (0 to -1°C) to begin the rainfall simulation. Treatments with crop residues added were removed from the freezers 5-7 h earlier than those without residues to allow for slower thawing. All water used for prewetting and for rainfall simulation was purified by reverse-osmosis and cooled to 3-5°C.

3.4.2 Rainfall Simulation

The design of the rainfall simulator was adapted from that used by Wright et al. (2006). A TeeJet3/8 HH-SS-24 WSQ nozzle was placed above the center of the system 3 m above the soil surfaces. This nozzle was operated at 28 kPa to deliver rainfall at approximately 30-35 mm h^{-1}. The relatively low intensity of the rainfall was selected to reflect runoff conditions more typical of prairie rainfall and snowmelt runoff conditions than the 75 mm h^{-1} that is often used in rainfall simulator studies. Soil trays were placed on an adjustable slope table that was adjusted to a slope of 3%; the shallow slope was selected to represent relatively level prairie landscapes. Also, in all cases, runoff water was cooled to 3-5°C to simulate the cold water temperatures that are likely to occur during snowmelt, the dominant type of runoff in the prairies (Nicholaichuk 1967; Glozier et al. 2006).

The interior of the soil boxes for the runoff studies was 0.3 m wide, 0.95 m long with a depth of 5 cm. The sides and bottoms of the soil trays were insulated with styrofoam to encourage frozen soils to thaw from the surface downwards, as under natural conditions. The soil trays consisted of two compartments, an upper compartment for the soil and an empty lower compartment, to allow pre-wetting of the soil samples from below through capillary rise and to collect percolate. The upper compartment was separated from the lower compartment by steel mesh covered with a plastic sheet with 25 mm diameter holes. Underlying the plastic sheet was a layer of inert filter cloth, below which was a 5 cm layer of styrofoam insulation, also with 25 mm holes that corresponded to the holes in the plastic sheet. Wooden frames with plastic mesh were placed on top of the soil trays to minimize the loss of vegetative residues with the runoff; otherwise these lost residues could have plugged the runoff collection pumping system. A coarse screen (6.35 mm mesh) was also used at the outlet end of the runoff box to prevent plugging of the runoff collection system. Since only soluble nutrients were measured in this experiment, the interference from these measures for retaining straw was probably minimal.

During each rainfall simulation event, runoff samples were collected at intervals of 0-15, 15-30 and 30-60 min, from the beginning of runoff. Runoff samples were weighed to calculate runoff volumes, thoroughly agitated and then sub-sampled; subsamples were immediately transported to the laboratory for water quality analyses.

3.4.3 Analyses of Water samples

Soluble reactive phosphorus (SRP) in runoff samples were determined using the ascorbic acid-molybdate blue method (Murphy and Riley 1962) after filtering to 0.45 μm.

3.4.4 Statistical Analysis

Statistical analysis was completed using the GLM option of ANOVA in Statistical Analysis Software (SAS). Descriptive statistics were used to test the data for normality and skewness using Proc Univariate of SAS. Runoff water quality data were not normally distributed, with negative skewness (results not presented). Therefore, the data were transformed using logarithms. Statistical analyses of the log-transformed data produced results that were different from those of the non-transformed data. Therefore, the data and statistical analyses presented, including treatment means, are for the log-transformed data. The experiment's factorial design was used to test for interactions between effects of soil, crop residue and freezing-thawing.

3.5 Results and Discussion

3.5.1 Soluble Reactive P Concentration in Simulated Runoff from Soil, Residue and Freezing Treatments

Although the overall geometric mean SRP concentrations in runoff appeared to be 14 times higher for the soil with higher soil test P than for the soil with lower soil test P, there was an interaction between soil test effect and freezing for this runoff collection period (Table 3.3). In runoff from unfrozen soils, the average mean SRP concentration from soil with higher soil test P was approximately 37 times greater than from soil with lower soil test P. However, in runoff from frozen soils there was no significant difference in SRP concentration from these two soils.

The geometric mean of SRP lost to runoff in the presence of residue was approximately three times greater than in the absence of residue. However, the freezing treatment did not interact with residue treatment which means that freezing did not significantly affect the influence of residue on SRP losses or vice versa (Table 3.3) in spite of the significant effect of freezing on P release from residues in other studies (Appendix C; Bechmann et al. 2005; Roberson et al. 2007).

Table 3.3. Soluble reactive P (SRP) concentration in simulated runoff from soil, residue and freezing treatments (geometric means).

Group means	Treatment[z]			First Interval (0-15 minute)	Second Interval (15-30 minute)	Third Interval (30-60 minute)	Overall Flow Weighted Mean (0-60 minute)
				µg L^{-1}			
Soil P	MHP			5.5	4.2 *b*	3.2 *b*	5.4
	VHP			77.5	44.5 *a*	32.1 *a*	62.2
Residue	-R			11.5 *b*[y]	14.2	14.3	14.7
	+R			36.9 *a*	13.3	7.2	23.0
Freezing	-F			27.4	15.8	10.7	23.1
	+F			15.5	11.9	9.7	14.6
Soil P X Freezing	MHP		-F	4.5 *c*	3.8	2.7	4.4 *b*
	MHP		+F	6.8 *bc*	4.6	3.8	6.6 *ab*
	VHP		-F	168 *a*	64.6	42.1	119 *a*
	VHP		+F	35.7 *ab*	30.6	24.4	32.3 *a*
Soil P X Residue	MHP		-R	2.4	3.3	3.8	3.7
	MHP		+R	12.2	5.4	2.7	8.0
	VHP		-R	53.8	61.1	53.4	58.6
	VHP		+R	111.5	32.3	19.2	66.0
Freezing X Residue	-F		-R	12.0	15.6	14.2	15.6
	-F		+R	62.5	16.0	8.0	34.4
	+F		-R	11.0	13.0	14.3	13.9
	+F		+R	21.8	11.0	6.5	15.3
Soil P X Freezing X Residue	MHP	-F	-R	2.4	3.1	2.7	3.3
	MHP	-F	+R	8.2	4.7	2.7	6.0
	MHP	+F	-R	2.5	3.5	5.4	4.1
	MHP	+F	+R	18.1	6.2	2.7	10.5
	VHP	-F	-R	59.6	77.7	74.8	73.4
	VHP	-F	+R	474.6	53.8	23.7	195.1
	VHP	+F	-R	48.6	48.0	38.2	46.7
	VHP	+F	+R	26.2	19.4	15.6	22.3

Analyses of variances applied to log transformed values for all data	df	P > F	P > F	P > F	P > F
Soil P	1	<0.0001	<0.0001	<0.0001	<0.0001
Residue	1	0.014	0.835	0.067	0.245
Freezing	1	0.207	0.403	0.790	0.230
Soil P X Freezing	1	0.035	0.164	0.214	0.032
Soil P X Residue	1	0.337	0.096	0.336	0.393
Freezing X Residue	1	0.284	0.768	0.767	0.363
Soil P X Freezing X Residue	1	0.061	0.608	0.516	0.183
CV (%)		41	35	43	36

[z] VHP = high soil test P; MHP = low soil test P; +R = with residue; -R = without residue; +F = subjected to freezing; -F = not subjected to freezing.

[y] Mean values followed by the same letter within a column for a group of means are not significantly different.

In the second and third intervals, soil test P was the only factor that significantly affected the concentration of SRP in runoff. The geometric mean of SRP concentration in runoff was approximately 10 times higher for the soil with very high soil test P than for the soil with medium-high soil test P. This difference was less than the overall average difference between the two soils in the first interval and was not affected by an interaction with freezing. Also, the concentration of SRP in runoff from treatment where residues were added appeared to decline during the second and third intervals, indicating that the influence of residues on P loss appeared to diminish as the runoff trial progressed.

The geometric mean values of the SRP lost in runoff collected during the entire runoff period followed the same trend as in the first interval, except that residue treatment had no significant effect on the SRP lost in runoff in the entire runoff period.

In the first interval, the interaction between soil test P and freezing indicated that freezing eliminated the substantial difference in runoff SRP concentrations for these two soils in the unfrozen state. The most likely reason for this lack of difference between the two frozen soils is that only a few mm of the soil surface melted during the entire period of runoff collection (for example, frozen soils had to be thawed for 24 h after the runoff trial before the soil could be removed from the trays). Therefore, with only a few mm of soil depth to interact with runoff, less SRP was extracted with the runoff from the frozen soil due to less interaction between runoff water and soil. Sharpley (1985) reported that the effective depth of interaction (EDI) between soil surface and runoff plays an important role in determining P losses to surface runoff. Although neither we nor Sharpley quantitatively measured the effect of soil freezing on EDI, we can assume that this factor plays an important role in runoff over frozen soils.

The effect of soil test P on the SRP lost to runoff was most obvious in the second and third interval where soil P did not interact with either of the other two factors. Other studies have also shown that total dissolved phosphorus (TDP) and SRP concentrations in runoff are highly dependent on soil test P concentrations (Sharpley et al. 1977, 1978, 1994; Daniel et al. 1994; Pote et al. 1996, 1999; Tarkalson et al. 2004).

The difference in SRP concentration in runoff from the soils may also be related to soil organic matter content. Soil organic matter contents were 4.8 and 2.4 % for the soils with very high and medium to high soil test P, respectively. The higher soil organic matter content in the soils with higher soil test P may have increased the P losses by increasing shallow infiltration into the soil surface and the effective depth of interaction between runoff water and soil.

Except for the frozen soil in the first interval, there was a consistent and substantial difference between the SRP concentration in runoff from the soil with very high soil test P and the soil with medium to high soil test P (Table 3.3). However, the SRP lost from both soils was much lower than expected based upon the equation for the correlation between Olsen P (mg kg^{-1}) and SRP loss (mg L^{-1}) with simulated runoff (SRP = 0.0073(Olsen P)+0.1288) for Manitoba soils measured by Sawka et al. (2007). The comparison between the results of the SRP concentration in runoff for the period of 0-30 minutes showed that in the unfrozen soil with lower soil test P, the SRP concentration was 2.75 $\mu g\ L^{-1}$ compared to 245 $\mu g\ L^{-1}$ as predicted by Sawka et al. (2007). In the soil with very high soil test P, the concentration of SRP was 69 $\mu g\ L^{-1}$ compared to the predicted value 486 $\mu g\ L^{-1}$. These disparities in the SRP concentration could be due to the differences in the methods used in each study. For example, we used lower rainfall intensity, shallower soil depth, cooler water, a shallower slope and narrower soil compartments than those used in Sawka et al. (2007). However, the reasons for a 20 fold increase in SRP concentration for the higher P soil, when only a two fold increase was expected, are not known.

The first interval was the only period where crop residues significantly increased the concentration of SRP lost in runoff. The confinement of the residue effect to the first interval alone could be because the majority of the residue P was easily released and washed out at the beginning of runoff, which led to no significant losses in the following intervals of runoff. Complementary results were mentioned by Schreiber (1985) who also observed rapid increase in P losses from vegetative residue during rainfall simulation, followed by decreases with time. The author noted that the large losses of P in the initial period probably represented removal of easily released nutrients from the surface of residues.

3.5.2 Soluble Reactive P Concentration in Percolated Water from Soil, Residue and Freezing Treatments

The concentrations of SRP losses with percolate water were influenced by a three-way interaction between soil P, residue and freezing (Table 3.4). However, these factors had inconsistent effects on the percolate SRP losses, except for soil test P. Therefore, in all cases where freezing and residue treatments were equivalent, the percolate losses of P were much higher for soil with higher P than for soil with lower P. Adding residues reduced SRP losses from the unfrozen MHP soil and increased SRP losses when this soil was frozen. However, residues had no effect on both frozen and unfrozen VHP soil. Freezing increased SRP losses only in the MHP when covered by residues. However, freezing reduced SRP losses from the two soils when not covered by residues and had no effect on the covered VHP soil.

In the soil with higher soil test P, presence of residue in frozen or unfrozen soil conditions did not affect the concentrations of SRP losses with percolate, perhaps because the release of P from soil predominated over that from vegetative residues. Presence of residue in unfrozen MHP soil may be reduced rain drop effect on soil surface resulting of decreasing the percolate SRP losses in this situation. However, more P was released in the presence of residue on the surface of the frozen MHP soil, probably due to influence of freezing treatment on release of residue tissue P.

Table 3.4. Soluble reactive P (SRP) concentration in percolate water from soil, residue and freezing treatments (geometric means).

Group means	Treatment[z]			SRP loss with percolate
				—— $\mu g\ L^{-1}$ ——
Soil P		MHP		29
		VHP		436
Residue		-R		140
		+R		90
Freezing		-F		97
		+F		130
Soil P X Freezing	MHP		-F	14
	MHP		+F	57
	VHP		-F	668
	VHP		+F	293
Soil P X Residue	MHP		-R	45
	MHP		+R	18
	VHP		-R	432
	VHP		+R	453
Freezing X Residue	-F		-R	238
	-F		+R	39
	+F		-R	82
	+F		+R	206
Soil P X Freezing X Residue	MHP	-F	-R	76 *d*[y]
	MHP	-F	+R	3 *f*
	MHP	+F	-R	27*e*
	MHP	+F	+R	124 *cd*
	VHP	-F	-R	749 *a*
	VHP	-F	+R	597 *ab*
	VHP	+F	-R	250 bc
	VHP	+F	+R	344ab

Analyses of variances applied to log transformed values for all data	df	P > F
Soil P	1	<0.0001
Residue	1	0.073
Freezing	1	0.222
Soil P X Freezing	1	0.001
Soil P X Residue	1	0.0491
Freezing X Residue	1	<0.0001
Soil P X Freezing X Residue	1	0.0001
CV (%)		14

[z] VHP = high soil test P; MHP = low soil test P; +R = with residue; -R = without residue; +F = subjected to freezing; -F = not subjected to freezing.

[y] Mean values followed by the same letter within a column for a group of means are not significantly different.

For the both soils with MHP and VHP, freezing of uncovered soil significantly reduced the percolate P loss as SRP. The SRP lost from the two soils before freezing was approximately three times greater than the SRP lost after freezing. These decreases in SRP losses from both uncovered soils when frozen were probably due to the effect of reduced interaction between frozen soil and percolating water, similar to the effect on runoff losses, already discussed.

3.5.3 Volume of Runoff and Percolate Collected in Simulated Runoff Experiment

None of the treatment factors (soil P, residue and freezing) affected the volume of water that percolated through the soil (Table 3.4). In all cases the majority of the water collected from the trays was collected as surface runoff. In two of four cases, runoff from the higher P soil was less than from lower P soil. The higher P soil produced less runoff than the lower P soil when the unfrozen soils were covered by residues and when the frozen soils were not covered by residues. However, the runoff volumes from the soil with higher and lower soil test P were not significantly different when residue cover was combined with freezing and when neither covered or frozen.

Adding residues reduced runoff volumes from the frozen MHP soil and in the unfrozen VHP soil. Freezing reduced runoff volume only in the high P soils when not covered by residues and in low P soils when covered by residues.

The interactions between soil P, residue and freezing indicate that none of these factors had a consistent effect on runoff volume. The soil with high soil test P contained about twice as much soil organic matter as the low P soil (Table 3.1). This high organic matter content may have increased infiltration rates and water holding capacity (Hudson 1994).

Table 3.5. Volume of runoff and percolate collected in simulated runoff experiment (geometric means).

Group means	Treatment[z]			Percolated water (0-60 minute)	Runoff water (0-60 minute)
				L	L
Soil P		MHP		14.6	23.5
		VHP		12.8	22.6
Residue		-R		12.8	23.5
		+R		14.6	22.6
Freezing		-F		13.9	23.4
		+F		13.5	22.7
Soil P X Freezing	MHP		-F	14.7	23.6
	MHP		+F	14.5	23.4
	VHP		-F	13.2	23.2
	VHP		+F	12.5	22.1
Soil P X Residue	MHP		-R	13.1	24.0
	MHP		+R	16.2	23.0
	VHP		-R	12.6	23.1
	VHP		+R	13.1	22.1
Freezing X Residue	-F		-R	12.4	24.1
	-F		+R	15.5	22.7
	+F		-R	13.3	23.0
	+F		+R	13.7	22.5
Soil P X Freezing X Residue	MHP	-F	-R	13.3	23.6 *a*[y]
	MHP	-F	+R	16.2	23.6 *a*
	MHP	+F	-R	13.0	24.4 *a*
	MHP	+F	+R	16.2	22.5 *b*
	VHP	-F	-R	11.7	24.6 *a*
	VHP	-F	+R	11.6	21.8 *b*
	VHP	+F	-R	13.6	21.7 *b*
	VHP	+F	+R	14.9	22.5 *b*

Analyses of variances applied to log transformed values for all data	df	P > F	P > F
Soil P	1	0.154	0.032
Residue	1	0.146	0.027
Freezing	1	0.729	0.106
Soil P X Freezing	1	0.822	0.266
Soil P X Residue	1	0.331	0.966
Freezing X Residue	1	0.281	0.320
Soil P X Freezing X Residue	1	0.226	0.002
CV (%)		9	1.5

[z] VHP = high soil test P; MHP = low soil test P; +R = with residue; -R = without residue; +F = subjected to freezing; -F = not subjected to freezing.

[y] Mean values followed by the same letter within a column for a group of means are not significantly different.

The most surprising result was the lack of a freezing effect on runoff and percolate volumes. Freezing was expected to substantially increase the runoff volumes and decrease percolate volumes due to decreased infiltration. Indeed, as mentioned earlier, frozen trays required an additional 24 h of thawing after the runoff trial before the soil could be removed from the trays. However, freezing reduced runoff volumes in half of the treatments and had no effect in the others. The inconsistent and unexpected effects of the freezing treatment on runoff could have been caused by preferential flow through or around the runoff boxes. Even though ice closes the majority of soil pores, a small portion of meltwater is able to percolate through the frozen layer through air-filled pores (Stadler et al. 1996). However, in our result the percolated water accounted for at least 30% of the water lost from both frozen and unfrozen soils (Table 3.4). These high percentages of percolates indicate that there was probably substantial preferential flow, probably through cracks in soil and/or gaps between the soil and interior walls of the boxes.

3.5.4 Soluble Reactive P Export Loads from Soil, Residue and Freezing Treatments Subjected to Simulated Runoff.

The runoff losses of SRP expressed per unit area of soil (g P ha^{-1}) during each of the runoff intervals (Table 3.5) was generally similar to the results for SRP concentration in runoff.

Table 3.6. Soluble reactive P (SRP) export loads from soil, residue and freezing treatments subjected to simulated runoff (geometric means).

Group means	Treatment[z]			Runoff loss (0-60 minute)	Percolate loss (0-60 minute)	Total loss (runoff + percolate)
				g ha^{-1}		
Soil P		MHP		4.5	8.9	20
		VHP		49	200	274
Residue		-R		12	38	59
		+R		18	46	92
Freezing		-F		19	47	86
		+F		11	37	64
Soil P X Freezing	MHP		-F	3.7 *a*[y]	7.3	16
	MHP		+F	5.4 *a*	11	25
	VHP		-F	97 *b*	310	449
	VHP		+F	25 *b*	129	168
Soil P X Residue	MHP		-R	3.7	7.7	14
	MHP		+R	6.4	10	28
	VHP		-R	47	191	245
	VHP		+R	51	210	307
Freezing X Residue	-F		-R	13	104	121
	-F		+R	27	22	61
	+F		-R	11	14	29
	+F		+R	12	100	140
Soil P X Freezing X Residue	MHP	-F	-R	2.7	35 *b*	38 *d*
	MHP	-F	+R	5.0	1.5 *a*	7.0 *e*
	MHP	+F	-R	3.5	1.6 *a*	5.5 *e*
	MHP	+F	+R	8.3	71 *bc*	110 *c*
	VHP	-F	-R	63	307 *d*	379 *ab*
	VHP	-F	+R	150	313 *d*	531 *a*
	VHP	+F	-R	36	119 *c*	158 *bc*
	VHP	+F	+R	18	140 *cd*	178 *bc*

Analyses of variances applied to log transformed values for all data	df	P > F	P > F	P > F
Soil P	1	<0.0001	<0.0001	<0.0001
Residue	1	0.288	0.355	0.022
Freezing	1	0.201	0.251	0.116
Soil P X Freezing	1	0.028	0.004	0.0008
Soil P X Residue	1	0.389	0.624	0.252
Freezing X Residue	1	0.385	<0.0001	<0.0001
Soil P X Freezing X Residue	1	0.235	<0.0001	<0.0001
CV (%)		98	15	12

[z] VHP = high soil test P; MHP = low soil test P; +R = with residue; -R = without residue; +F = subjected to freezing; -F = not subjected to freezing.

[y] Mean values followed by the same letter within a column for a group of means are not significantly different.

The effect of soil P on P export was influenced by an interaction with freezing that followed a similar overall pattern as for SRP concentration in runoff. However, the interaction was not identical in both cases. Exports of P from the soil with higher P were significantly higher than exports from the soil with lower P, regardless of freezing treatment.

Due to much higher concentrations of SRP in percolate than in runoff, overall losses of SRP as percolate were much greater than runoff losses from runoff when both were expressed on an area basis (Table 3.5). Losses of SRP with percolate water were influenced by a three-way interaction between soil P, residue and freezing. As expected, the percolate losses of P were much higher for soil with higher P than for soil with lower P in most cases. However, this was not the case in frozen soils covered with residues.

For unfrozen soils, the export of P from the soil with higher P was 26 times greater than that from the soil with lower P, whereas the difference was only 5 fold when the soils were frozen. In general, the lower runoff volume from the soil with higher soil test P offset some of the higher concentrations of SRP in runoff when export loads were calculated.

The effects of residues and freezing on percolate losses of P were also inconsistent. Adding residues decreased percolate P losses in lower P soils that were unfrozen, increased losses in lower P soils that were frozen and had no effect on high P soils. Freezing decreased percolate losses of P for lower P soils without residues, but increased losses for lower P soils that were covered by residues and had no effect on high P soils covered by residues.

Given the high proportion of P losses in percolate and the similarity in the overall ranking of treatments for runoff losses and percolate losses, the combined losses of SRP from both modes of transport followed a pattern that was similar to that for percolate losses. Combined losses of SRP were also influenced by a three-way interaction between soil, residue and freezing. Differences in total losses of SRP among treatments were similar to those for percolate P except that freezing reduced total P losses in higher P soils that were covered by residues and had no effect on higher P soils that were not covered by residues.

However, in three of four cases, where equivalent residue and freezing treatments were compared, total SRP export was substantially greater from the soil with higher P. Adding residues to unfrozen soil with lower soil test P decreased percolate and total export loads of SRP. This decrease may have been due to reduced impact of rain drops on the soil surface. However, adding residues to this soil under frozen conditions increased the percolate and total export loads of SRP. In this case the increased losses may have been caused by wetting, freezing and thawing causing rupturing of plant cells and increasing release of vegetative P. This mechanism is supported by the observations of Bechmann et al. (2005) who measured greater losses of SRP from catch crop soils when those soils were exposed to freezing and thawing cycles.

In the soil with higher soil test P, presence of residue in frozen or unfrozen soil condition did not affect the percolate and total export loads of SRP lost, probably because the release of P from soil predominated over that from vegetative residues. For the lower P soil, freezing of uncovered soil significantly reduced the percolate P loss as SRP and also reduced the total export loads of SRP. The export of percolate and total (runoff + percolate) SRP lost before freezing was approximately 23 and 7 times greater than the SRP lost after freezing respectively. For uncovered soil with higher P, the export of percolate SRP before freezing was approximately 3 times greater than after freezing; however, freezing did not affect total export of SRP in this situation. These decreases in SRP export from both uncovered soils when frozen were probably due to the effect of reduced interaction between frozen soil and percolating water, similar to the effect on runoff losses, already discussed. Another possible reason for these observations is that freezing and thawing could have increased the buffering capacity of the top few mm of melted surface soils which led to stranger retention of P in the soil. For example, Wang et al. (2007) found that freezing and thawing increased the buffering capacity of soil, compared to an unfrozen treatment. In the contrast, Bechmann et al. (2005) measured little effect of freezing and thawing on SRP losses from bare soil.

3.6 Conclusions

The majority of the P loss from residue occurs at the beginning of a runoff event, because the residue P is highly soluble. Even though this loss occurs over a short period, it accounts for a significant portion of total SRP losses from the system. This contribution is relatively unaffected by freezing. However, since the influence of soil test P is reduced in frozen soils, the proportion of total SRP loss in runoff that can be attributed to vegetative P is likely to increase when runoff occurs over frozen soils, especially if runoff volumes are small. When runoff and percolate losses of SRP are considered together, the influence of residue P on concentration and export of SRP depends on soil test P concentration and soil freezing and are not consistent.

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CHAPTER 4

OVERALL SYNTHESIS

Phosphorus (P) is the most limiting nutrient in many water bodies and a small, agronomically insignificant loss of agricultural P can pose a high risk of water quality degradation. There are two groups of factors controlling the P loss, source factors and transport factors. Source factors are divided into two types, point sources and non-point sources. Agricultural non-point sources are the most challenging for water quality due to the difficulties of controlling these sources. This project focused mainly on the effect of freezing and thawing on the loss of P from the two most important non-point sources, vegetative P and soil P on agricultural land.

The overall aims of this thesis were to: 1) predict the potential risk of the P losses from vegetative residues in two different tillage (zero-till and conventional tillage) and two cropping systems (perennial forge and annual crops) under freezing and thawing condition to imitate the natural cold climate in the most Canadian prairies; 2) investigate the effect of water:residue ratio on the concentration of P extracted from vegetative residues; this information is useful to understand the impact of different amounts of runoff interacting with vegetative residues, as a result of weather or landscape position effects on the volume of snowmelt interacting with the residues; 3) explore the effect of the interaction between soil and vegetative residue on the P losses. Although we have traditionally focused on the benefits of vegetative residues to intercept nutrients lost from soil, perhaps we need to consider the benefits of soil to intercept the nutrients lost from vegetation. Therefore, the interactions between vegetative residues and surface soil during snowmelt, including reiterative cycles of retention, mobilization, and transfer deserve more investigation, as we try to develop sound BMPs for the reduction of nutrient loading of surface water.

The results of the first experiment (Chapter 2) where vegetative residues were exposed to wetting freezing and thawing, indicate that the potential losses of SRP from residues in zero-till is significantly higher than those in a conventionally tilled field. Also, potential losses were significantly higher from perennial forage compared to the annual crop. Generally, residue biomass content was a key factor controlling the amount of extracted vegetative P. Within cropped areas of fields, zero-tillage and perennial forages were consistently associated with higher biomass compared to conventional till and annual crops systems. These higher biomass weights increase the amount of water extractable P on top of the soil surface and as result, a greater potential risk of P losses with snowmelt runoff. Therefore, the results from the first experiment (Chapter 2) indicate that the use of zero-tillage (ZT) for reducing soil erosion and the losses of PP may not reduce total losses of P in the Canadian prairies, because snowmelt over frozen and thawed plant residues and nearly level landscapes plays an important role, making losses of SRP from vegetative residues the major form of the P loss (Hansen et al. 2000; Little et al. 2007). These results also indicate that biomass and extractable vegetative P were uniform among landscape positions within the cropped portion of these fields.

The possible effect of the water volume on the vegetative P extraction was also investigated in the first experiment (Chapter 2). The results indicated that the concentration of the SRP extraction in 1.85 L water (equivalent to 1.5 cm of runoff) was approximately two times higher than that extracted by using 3.7 L water (Figure 2.5). Thus, in dry areas, such as the prairies, even low quantities of runoff would produce high concentrations of P that could be delivered to surface water.

The effect of interactions between soil, residue and freezing and runoff water were not measured in the first experiment, but formed the main objective for the second experiment (Chapter 3). Although the effect of residues on runoff P losses was short-lived and the effect of freezing was inconsistent, soil test P concentration generally played a large role in determining SRP concentration and overall losses in runoff water. In most cases the absolute concentrations of SRP were lower but the relative differences in runoff P concentration due to differences in soil test P were greater than had been measured in previous runoff simulation studies with Manitoba soils (Sawka et al. 2007). Given that the differences in the soil test P concentrations also reflected differences in landscape position and soil organic matter, all three factors may have a complex effect on P loss.

These experiments demonstrated that, under freezing and thawing conditions, the loss of P from soil and vegetative residues could be sufficient to promote eutrophication in surface water. However, during natural snowmelt runoff events, the interactions between these sources would be an important process for mitigating the high risk of P losses from agricultural and non-agricultural land. These studies also demonstrated that soil test P concentration is the dominant factor controlling losses of SRP to surface water under most laboratory conditions; however, the contribution of vegetative P to SRP concentrations in runoff is substantial at the beginning of runoff events, especially when vegetative residues are left on the surface. When runoff and percolate of SRP are considered together, the contribution of vegetative P is overshadowed in most cases by soil P. In a field with very high soil test P the majority of the SRP loss is likely to be from the soil; therefore, vegetative residues are unlikely to have a substantial and consistent effect. For soils with medium or low soil test P, the contribution of vegetative P to SRP losses by percolation and runoff could be substantial, especially after freezing and thawing. However, since SRP losses in runoff are of greatest concern for surface water quality, runoff losses are usually of greater concern than percolate losses or total combined losses from runoff and percolate.

In most cases SRP losses from soils with low or medium concentrations of soil test P will be much lower than from high P soils. Freezing played an important role for reducing the effect of soil test P on SRP losses from soils, likely by reducing the effective depth of interaction between soil and runoff water. However, maintaining medium or lower soil test P concentrations in agricultural land is probably a very important management practice for reducing SRP losses in runoff. The benefit of minimizing soil test P concentrations is likely to be greatest in lower slope positions. These areas often have higher soil test P than upland areas, due to a combination of natural processes and cultivation induced erosion. According to our simulated runoff experiment, the effect of soil test P on runoff SRP concentrations from lowland soils could be greater than for upland soils. These positions also include riparian areas when high quantities of vegetative biomass could release substantial amount of dissolved P during snowmelt. Furthermore, these areas are often more hydrologically active and more likely to interact with runoff than upland areas.

Our studies showed that vegetative residues increased SRP losses in the initial stages of runoff, regardless of soil test P or freezing-thawing cycles. However, when percolation losses and runoff losses are combined together, vegetative residues increased overall SRP losses from frozen soils with medium to high soil test P only, with no substantial or consistent effect on combined losses from soil with very high soil test P. Therefore, to prevent higher losses of total SRP by runoff alone or by the mentioned combined pathways, soil test P concentrations in ZT and PF fields must be lower than in CT and annual cropped fields. These strategies are likely to be most important on nearly level landscapes where most P loss is in dissolved rather than particulate form and in a dry cold climate when low volumes of snowmelt runoff are likely to deliver a high concentration of dissolved vegetative P to water bodies.

Further work will be required to characterize the loss of P from different types of vegetative residues and soils and from the interaction between these two sources under naturally frozen field conditions. For developing our knowledge of transport factors, field studies are required to eliminate some of the laboratory uncontrollable factors such as raindrop effect during simulated snowmelt, and preferential flow through or around the runoff boxes. Furthermore, SRP was the only form of P loss measured consistently in these laboratory experiments. Although this is the dominant form of P loss in Prairies, other forms of P in runoff may be very important in specific situations (e.g., PP on steep slopes).

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APPENDICES

Appendix A

SUPPLEMENTARY FIGURES AND TABLES FOR CHAPTER TWO

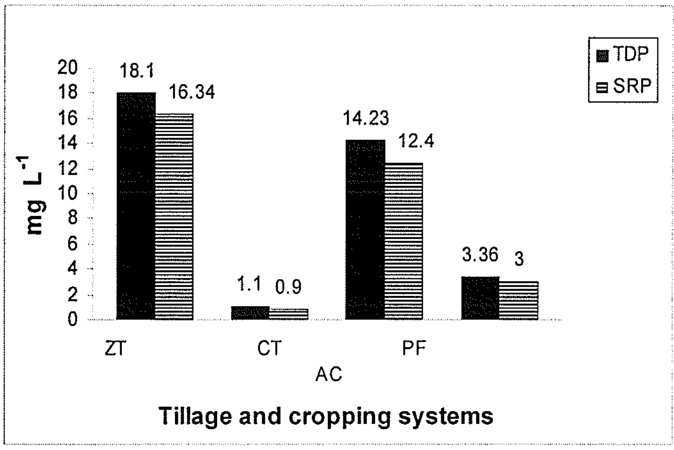


Fig A.1. Comparison between the extracted SRP and TDP from residue samples collected in 2006.

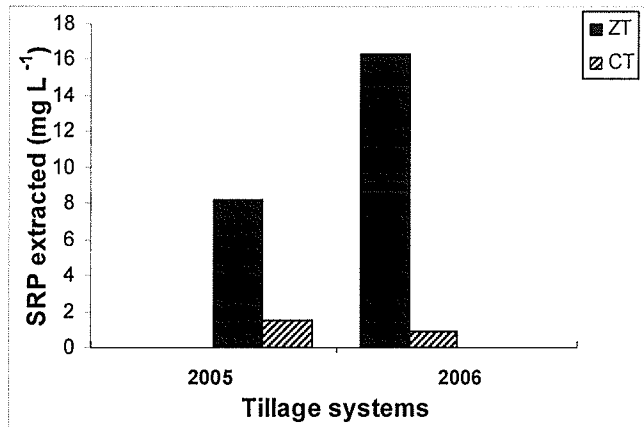


Fig. A.2. Comparison between the SRP extracted from residue samples collected in 2005 and 2006 from zero-till (ZT) and conventional tillage (CT).

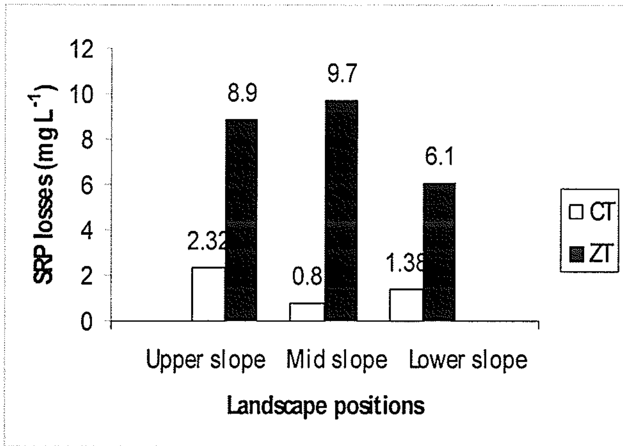


Fig. A.3. The average SRP extracted from vegetative residue in different landscape positions of zero-till (ZT) and conventional tillage (CT) in 2005.

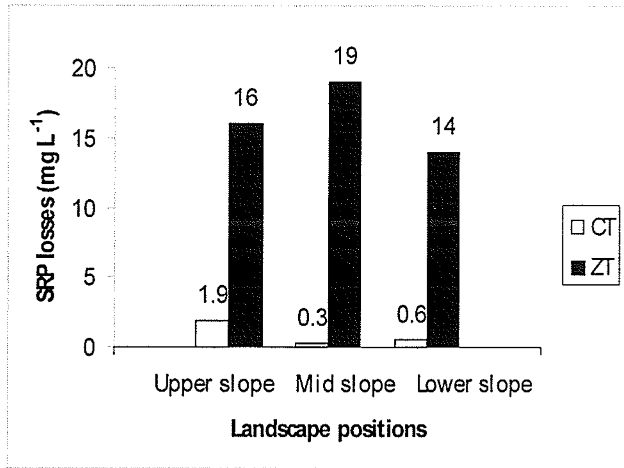


Fig. A.4. The average SRP extracted from vegetative residue in different landscape positions of zero-till (ZT) and conventional tillage (CT) in 2006.

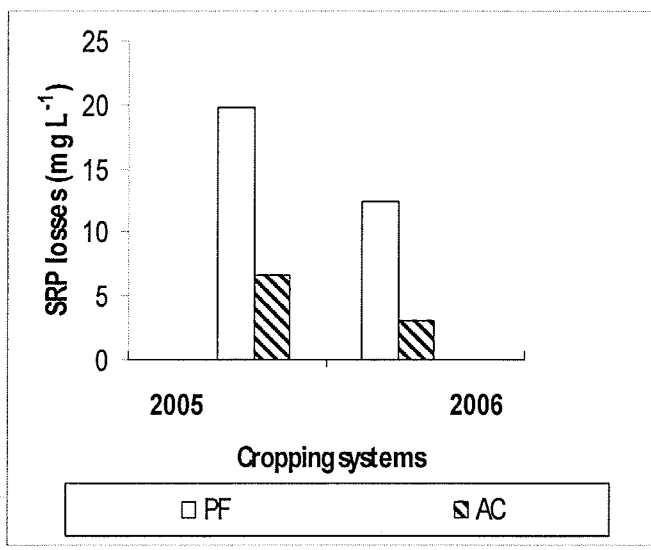


Fig. A.5. Comparison between the SRP extracted from vegetative residue in perennial forage (PF) and annual crops (AC) fields during (2005/06)

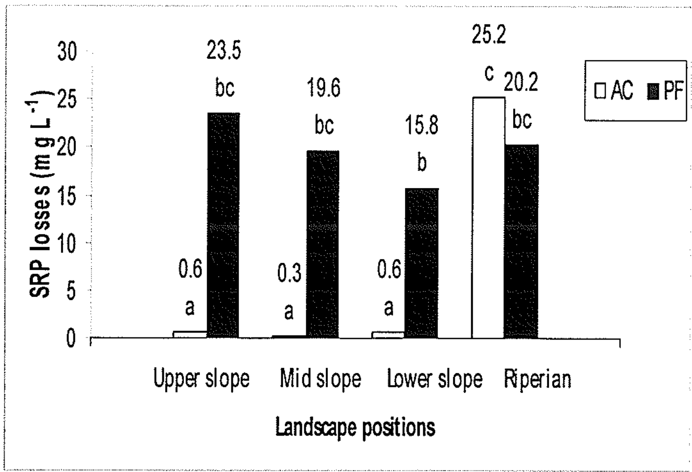


Fig. A.6. The average SRP extracted from vegetative residue in different landscape positions of perennial forage (PF) and annual crops (AC) in 2005.

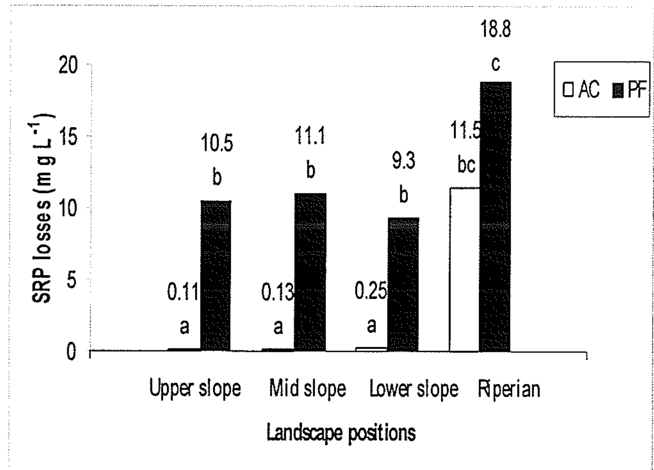


Fig. A.7. The average SRP extracted from vegetative residue in different landscape positions of perennial forage (PF) and annual crops (AC) in 2006.

Table B.1. Effect of field by landscape position interactions on the soluble reactive P (SRP) extractable from crop residues in perennial forage (PF) and annual crop (AC) fields, including riparian areas.

	Treatment		Sampling date Oct. 25, 2005				Sampling date Oct. 24, 2006			
	Field	Landscape Position	SRP		Residues biomass	SRP yield per kg biomass	SRP		Residues biomass	SRP yield per kg biomass
			mg L^{-1}	kg ha^{-1}	(T ha^{-1})	(mg kg^{-1})	mg L^{-1}	kg ha^{-1}	(T ha^{-1})	(mg kg^{-1})
Field X Landscape means	PF	Upper	23 *bc*	7.0 *bc*	4.2 *a*	1688 *c*	10.5	3.1	4.6	644 *b*
		Mid	19 *bc*	5.9 *bc*	4.9 *a*	1209 *b*	11.1	3.3	5.0	655 *b*
		Lower	15 *b*	4.7 *b*	4.4 *a*	1146 *b*	9.3	2.7	4.2	645 *b*
		Riparian	20 *bc*	6.0 *bc*	6.5 *c*	939 *b*	18.8	5.6	9.2	668 *b*
	AC	Upper	0.5 *a*	0.2 *a*	0.6 *b*	289 *a*	0.1	0.03	1.1	31.8 *a*
		Mid	0.3 *a*	0.1 *a*	0.7 *b*	149 *a*	0.1	0.04	0.9	44.4 *a*
		Lower	0.6 *a*	0.2 *a*	0.6 *b*	287 *a*	0.2	0.07	1.1	51.8 *a*
		Riparian	25.2 *c*	7.5 *c*	8.4 *bc*	978 *b*	11.5	3.4	5.4	648 *b*
ANOVA		df	P>F	P>F	P>F	P>F	P>F	P>F	P>F	P>F
Field* Landscape		3	0.0001	0.0001	0.002	0.0001	0.8	0.8	0.9	0.002

Table A.2. The effect of residue:water ratio on the concentration of SRP in extracts

Field	landscape	1.85 L water used for extraction	3.75 L water used for extraction
		SRP(mg L^{-1})	
F3-NE	Upper	3.96	1.802
F3-SW	Mid	26.80	13.534
F3-NW	Upper	0.786	0.380
F4-SW	lower	19.37	8.952
F4-NE	Mid	19.78	8.028
F4-NE	Upper	28.46	15.825
TWS- CT- Transect 2	lower	3.96	1.880
TWS- CT- Transect 4	lower	1.86	1.636
TWS- CT- Transect 4	Mid	2.04	1.636
TWS- ZT- Transect 4	lower	9.36	4.444
TWS- ZT- Transect 3	Upper	18.60	10.615
TWS- ZT- Transect 4	Upper	13.68	7.622

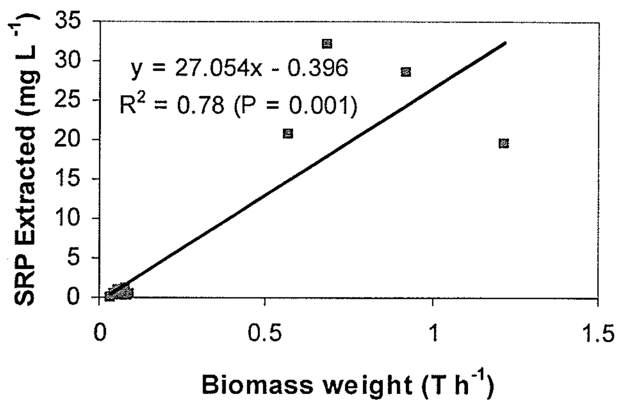


Fig. A.8. The correlation between SRP losses and biomass weight in the AC field including riparian areas (2005)

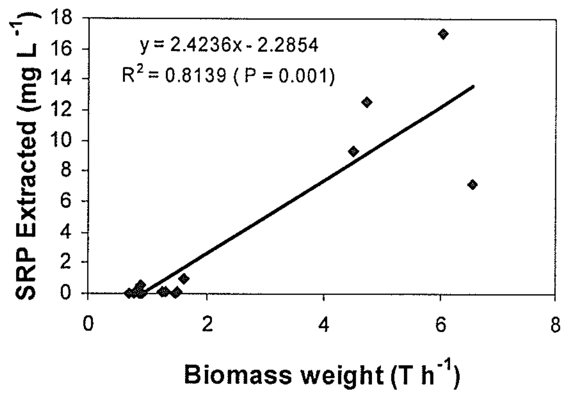


Fig. A.9. The correlation between SRP losses and biomass weight in the AC field including riparian areas (2006)

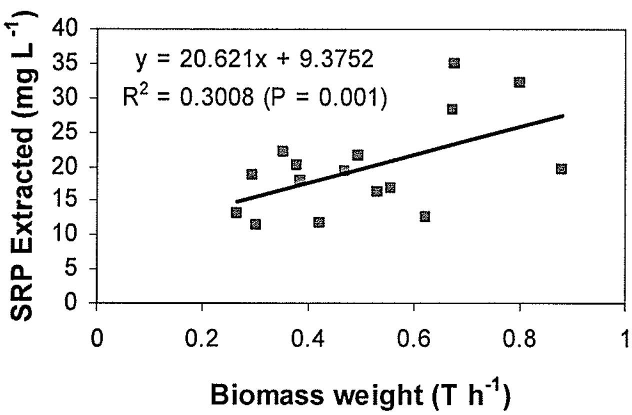


Fig. A.10. The correlation between SRP losses and biomass weight in the PF field including riparian areas (2005)

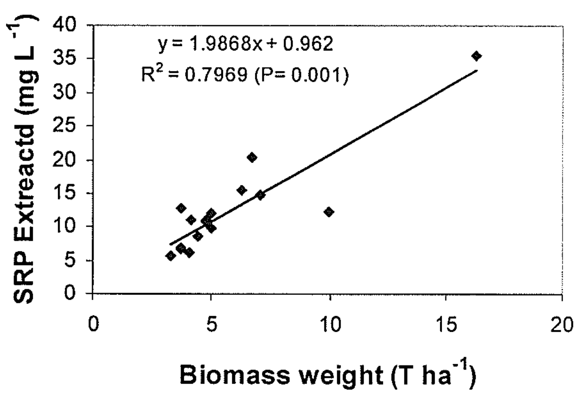


Fig. A.11. The correlation between SRP losses and biomass weight in the PF field including riparian areas (2006)

Table A.3. Nitrogen extracted from vegetative residue on wet weight basis ($\mu g\ L^{-1}$) in 2005 season						
Field	**slope**	**RES dry (g)**	**NO3**	**NO2**	**NH4**	**TDN**
TWS-ZT .Transect 2	U	156	0	14	5731.5	14560
F3-NE	M	12.94	0	1	103.5	432
TWS-ZT. Transect 4	U	192.35	0	5	1821.5	5810
F3-SW	U	10.91	0	1	22.5	604
TWS-CT .Transect 4	D	16.15	0	3	586.5	1870
F3-NW	D	5.12	1.5	0	39.5	221
F3-NW	R	304.7	0	26	9811.5	51210
F3-SW	M	10.07	3.5	1	166.5	430
TWS-ZT. Transect 2	M	171.4	0	12	6791.5	21760
F3-NW	M	13.15	0	-1	201.5	532
TWS-ZT. Transect 1	D	108.5	0	14	4591.5	14050
F3-SE	U	16.38	0	1	12.5	602
F3-SE	M	12.11	0	0	195.5	579
TWS-CT . Transect 4	M	22.13	0	2	193.5	1175
TWS-ZT. Transect 3	U	137	0	16	6111.5	18560
F3-NE	U	10.89	0	1	41.5	418
TWS-ZT. Transect 1	U	93.52	0	14	2351.5	6750
TWS-CT. Transect 2	D	32.32	0	3	2281.5	4090
TWS-ZT. Transect 1	M	140	0	10	3466.5	6970
TWS-ZT. Transect 4	M	76.41	0	8	1771.5	5490
F3-NE	R	354.3	0	26	14891.5	39910
F3-SE	R	121.62	0	26	3861.5	29510
TWS-CT. Transect 3	U	40.58	0	3	291.5	1225
F3-SW	D	11.96	0	0	103.5	527
F4-NW	U	97.43	0	13	8551.5	50360
F4-NW	D	129.3	0	14	6091.5	22510
F4-NE	R	220.1	0	23	10771.5	47260
F4-SW	U	213.75	0	27	24291.5	134410
F4-SE	R	146.2	0	23	17991.5	72410
F4-SW	R	125.5	0	21	2356.5	16910
F4-NE	M	76.47	0	13	10091.5	50060
F4-NW	M	123.95	0	21	13691.5	73160
F4-SW	D	139	0	27	15941.5	94910
TWS-ZT. Transect 3	M	220	0	15	7731.5	24610
TWS-CT. Transect 3	D	40.42	0	5	1626.5	4310
TWS-ZT. Transect 2	D	95.25	0	10	3201.5	12210
TWS-CT. Transect 1	M	55.62	0	3	1726.5	3580
TWS-CT. Transect 1	D	36.82	0	6	1886.5	4820
TWS-CT. Transect 2	M	23.49	0	3	1391.5	3025
F4-SE	U	125.3	0	21	19941.5	107660
TWS-CT. Transect 2	U	93.28	0	8	1981.5	6760
TWS-CT. Transect 1	U	79.31	0	5	806.5	2250
F4-SE	D	147.5	0	20	17641.5	67710
F4-NW	U	113.32	0	20	11866.5	58110
TWS-CT. Transect 3	M	17.02	0	1	181.5	1040
TWS-CT. Transect 4	U	12.25	0	0	-2.5	267

F4-NE	D	83.36	0	9	8291.5	36160
F4-SE	M	175.5	0	25	25891.5	124410
F3-NE	D	15.61	0	3	494.5	1135
F3-SW	R	174.92	0	34	8591.5	45310
F3-NW	U	9.43	30.5	5	169.5	485
TWS-ZT. Transect 3	D	80.02	0	4	1361.5	3960
F4-SW	M	124.9	0	19	14216.5	101160
F3-SE	D	13.1	0	1	-2.5	440
F4-NW	R	140.2	0	13	5171.5	29910
TWS-ZT. Transect 4	D	127.35	0	6	1841.5	5970

Table A.4. Nitrogen extracted from vegetative residue on wet weight basis ($\mu g\ L^{-1}$) in 2006 season					
Field	**Slope**	**RES dry (g)**	**NO2**	**NH4**	**TDN**
F3-SE	U	12.06	4	868	2530
F3-NE	M	11.53	0	0	281
F3-NE	R	136.36	34	1916	13430
TWS-ZT TR 2	D	153.32	36	39686	89555
TWS-CT TR2	U	47.73	10	4576	14875
F4-SW	D	53.05	23	18836	64555
F4-SW	U	65.09	21	17836	45655
F4-SE	U	75.33	23	14636	46755
TWS-ZT TR2	U	114.13	29	34286	112555
F4-NW	U	68.62	20	14086	59755
F4-SW	R	244.2	45	3736	19875
F4-SW	M	110.8	57	38386	174755
F3-SE	R	90.04	42	3501	25705
F4-SE	M	106.7	42	29736	96755
TWS-ZT TR3	U	129.71	32	34386	120355
F3-NW	U	12.65	1	0	534
F4-NE	U	118.2	59	43386	160555
F4-NW	R	132.5	41	7566	32355
F4-NE	R	94.48	33	8886	29955
F4-NW	D	81.44	42	24686	82855
F4-NE	D	87.85	36	24586	68255
F4-NE	M	81.8	34	17286	82155
F4-SE	D	98.27	21	20386	41755
F4-SE	R	418.6	87	38786	98755
F3-NE	U	21.28	3	0	1370
F3-NE	D	21.48	1	0	564
F3-SE	D	23.33	5	879	3490
F4-NW	M	69.08	24	14586	57155
TWS-CT TR4	M	21.47	4	2986	5935
TWS-CT TR2	M	29.22	4	3091	6465
TWS-CT TR1	D	26.99	6	4106	9415
TWS-CT TR4	U	27.83	7	5296	9715
TWS-ZT TR3	D	128.82	33	50686	141955
TWS-ZT TR4	D	176.25	31	16886	51955
TWS-ZT TR4	M	163.64	25	24711	74455
TWS-CT TR2	D	18.82	4	1489	3825
TWS-CT TR4	D	30.89	10	12186	38655
F3-SE	M	13.91	3	1513	3015
TWS-CT TR3	D	16.79	4	1666	5695
TWS-CT TR3	M	20.37	4	3651	7145
TWS-ZT TR1	U	125.59	21	18311	62455
TWS-ZT TR1	D	132.07	24	18861	55155
TWS-ZT TR4	U	87.61	29	19636	53255
F3-NW	M	10.725	1	189	668
TWS-ZT TR1	M	186.89	49	80186	219455
TWS-ZT TR2	M	128.04	24	21736	81955
TWS-ZT TR3	M	91.7	22	30386	87055
TWS-CT TR3	U	30.52	14	5486	17205

TWS-CT TR1	U	31.41	13	7011	19955
F3-NW	D	10.04	1	0	325
TWS-CT TR1	M	18.97	1	808	2125
F3-SW	M	17.19	1	-4	516
F3-NW	R	81.97	23	5726	21455
F3-SW	D	13.1	1	0	304
F3-SW	U	18.1	2	0	787
F3-SW	R	94.4	26	6006	36005

Appendix B

SUPPLEMENTARY FIGURES AND TABLES FOR CHAPTER THREE

Water preparation

All water used for prewetting and for rainfall simulation was purified by reverse-osmosis and cooled to 3-5°C by adding 200 L of ice to 500 L water in an insulated tank at least 5 hrs before the run. By the time of starting the run, water temperature in the tank was around 4 °C; however, it was around 7 °C at rainfall nozzle (Figure B.2).

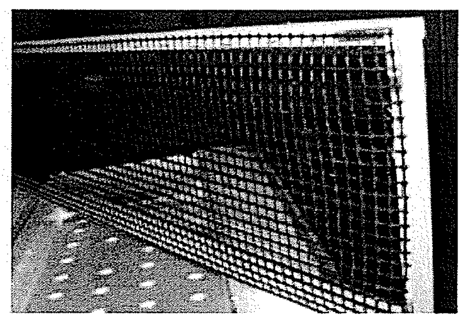
Ice inside the tank

Insulated tank

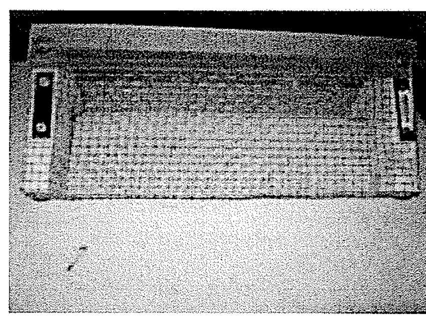
Fig. B.2. Prepare water

Soil trays preparation

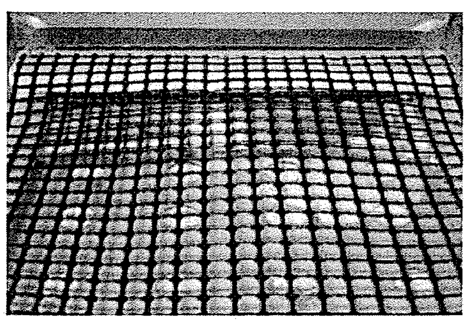
The interior of the soil boxes for the runoff studies was 0.3 m wide, 0.95 m long with a depth of 5 cm. The sides and bottoms of the soil trays were insulated with styrofoam to encourage frozen soils to thaw from the surface downwards, as under natural conditions. Also the bottom of soil trays was insulated by using a 5 cm layer of styrofoam insulation. The 25 mm holes made in the bottom styrofoam corresponded to the holes in the plastic sheet. Wooden frames with plastic mesh were placed on top of the soil trays to minimize the loss of vegetative residues with the runoff. A coarse screen (6.35 mm mesh) was also used at the end outlet of runoff water to prevent plugging of the runoff collection system (figure B.3).



Plastic mesh secured tightly on Wooden frame



A coarse screen filter used at the end outlet of runoff water



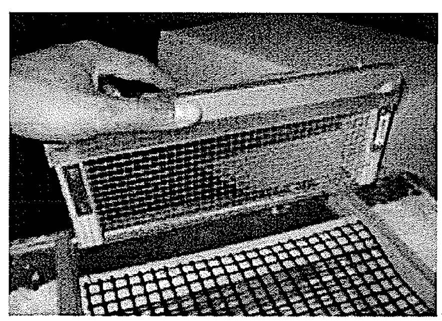
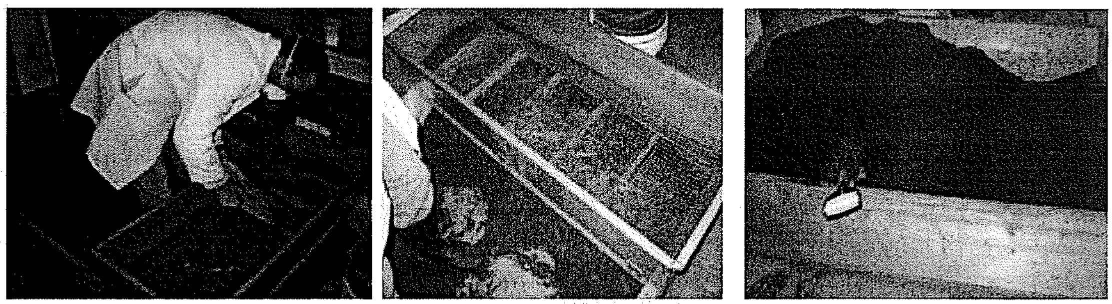


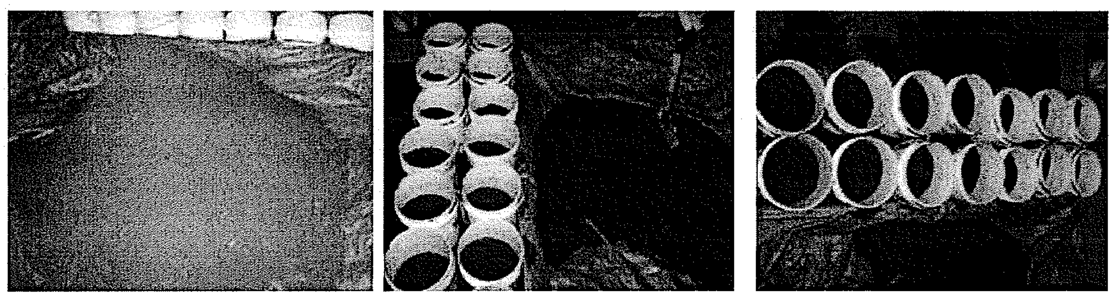
Fig. B.3. Prepare soil trays

Soil preparation

Soil was sieved twice through 10 mm mesh to ensure that soil aggregates were reasonably uniform in size. Each group of soil (MHP and VHP) was mixed thoroughly to make a uniform soil. Then all soils were replaced back into the buckets and stored before starting the rainfall simulation experiment (Figure B.4).



Sieving the soil Mixing the soil

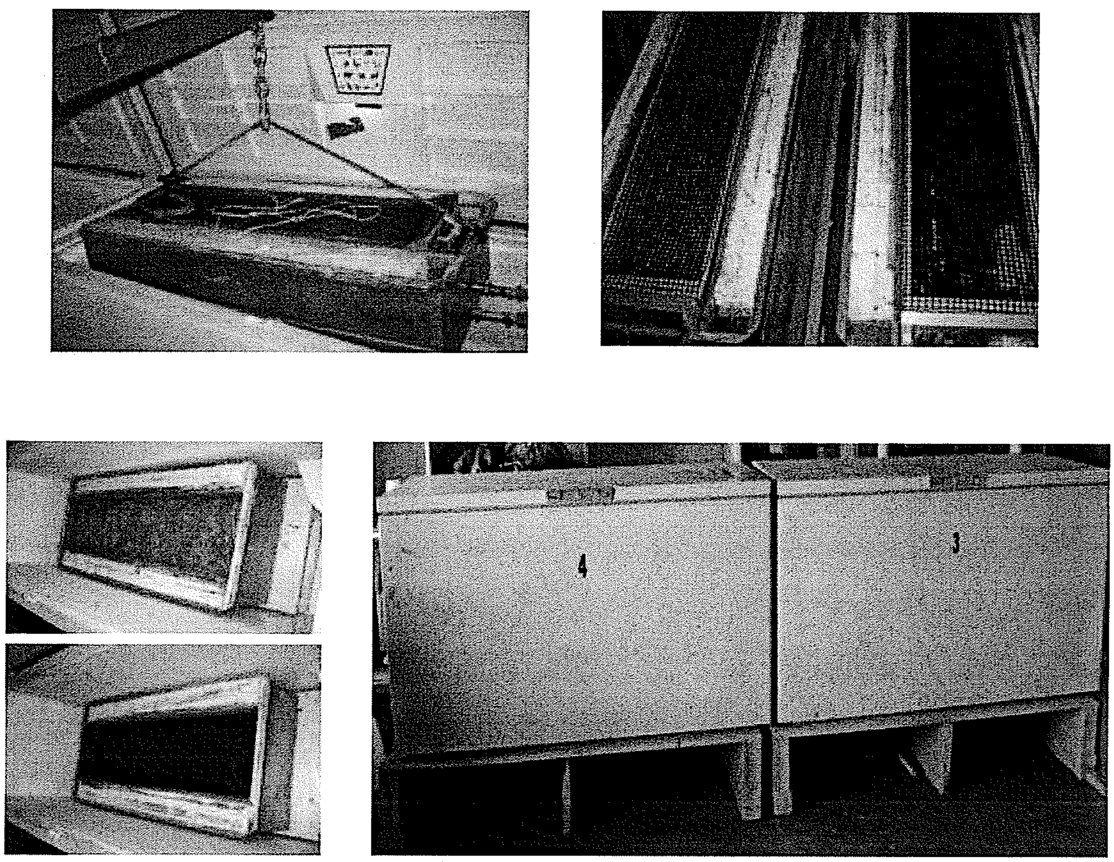


Replace the soil into the buckets

Fig. B.4. Prepare soil

Freezing the soils

The freezing treatment consisted of storing prewetted soil (with or without residues) in chest freezers at -15°C for 4 days. After 4 days, runoff boxes were taken out of the freezers for thawing. Digital thermometers were used to monitoring the changes of soil temperatures during the freezing period and to determine the time when soil temperature reached the desirable point (0 to -1°C) to begin the rainfall simulation. Treatments with crop residues added were removed from the freezers 5-7 h earlier than those without residues to allow for slower thawing.

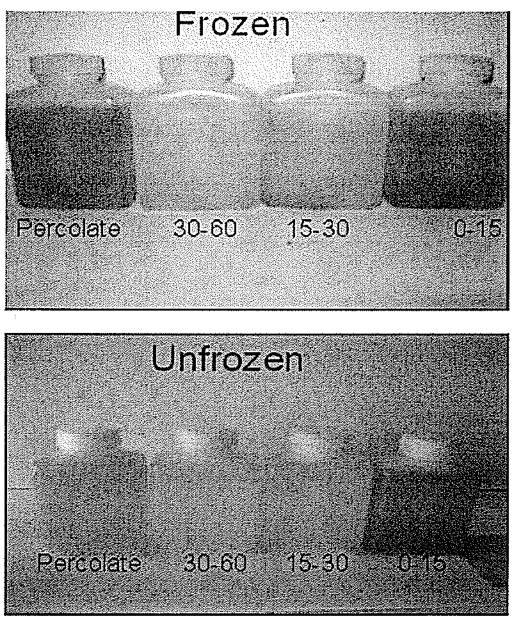


Soil trays inside freezers

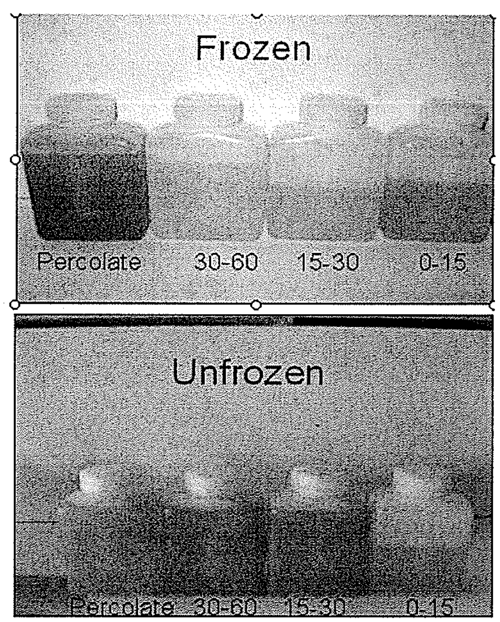
Fig. B. 5. Freeze the soils

Color of the water samples

There were differences in water color (for the both runoff and percolate water samples) between the samples collected from the soil with wheat residue cover and from the other soil without residue, and also between the samples collected from the soils under frozen and unfrozen treatments. The color was darker for the water collected from soil with wheat residue than that collected from the soil without what residue. Also, it was darker for the water collected from frozen soil than that collected from unfrozen soil. Furthermore, there were changes in the water color degrees during different durations in each individual run. In the first duration, the water color was darkest and it became lighter during the following durations (Figure B.6).



Water samples from soil with crop residue



Water samples from soil without crop residue

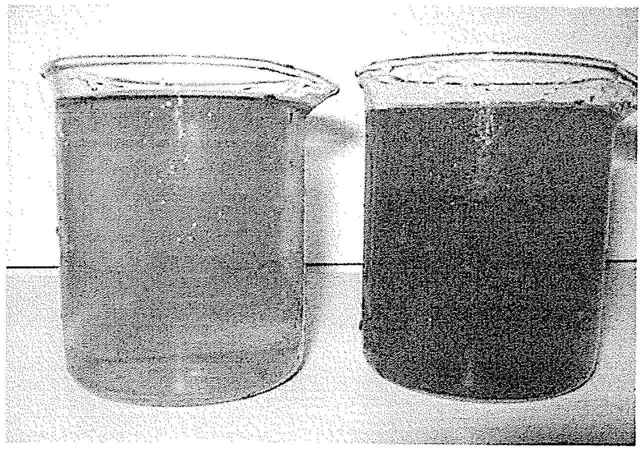


Fig. B. 6. Runoff and percolate water collection during rainfall simulation

Table B.1. Soluble reactive P (SRP) export from soil, residue and freezing treatments subjected to simulated runoff (arithmetic means).

Group means	Treatment			First Duration (0-15 minute)	Second Duration (15-30 minute)	Third Duration (30-60 minute)	Overall duration (0-60 minute)
				µg			
Soil P	+			1711.92	466.59	475.12	2653.69
	-			144.10	39.78	37.14	221.04
Residue	+			1642.17	208.82	170.81	2021.84
	-			213.86	297.55	341.45	852.89
Freezing	+			280.12	210.60	244.57	735.32
	-			1575.9	295.77	267.69	2139.41
Soil P X Freezing	-		-	81.62	34.72	30.63	146.99
	-		+	206.58	44.84	43.65	295.08
	+		-	3070.19	556.81	504.75	4131.83
	+		+	353.66	376.37	445.49	1175.55
Soil P X Residue	-		-	22.92	34.55	48.41	105.90
	-		+	265.29	45.01	25.87	336.18
	+		-	404.80	560.55	634.49	1599.89
	+		+	3019.05	372.63	315.74	3707.49
Freezing X Residue	-		-	246.23	369.74	427.82	1043.83
	-		+	2905.58	221.79	107.56	3235.00
	+		-	181.48	225.36	255.08	661.96
	+		+	378.75	195.84	234.05	808.67
Soil P X Freezing X Residue	-	-	-	25.46	28.25	33.27	86.99
	-	-	+	137.795	41.20	28.00	207.00
	-	+	-	20.382	40.86	63.55	124.80
	-	+	+	392.791	48.82	23.74	465.37
	+	-	-	467.01	711.23	822.38	2000.67
	+	-	+	5673.38	402.39	187.12	6263.00
	+	+	-	342.59	409.87	446.61	1199.12
	+	+	+	364.72	342.87	444.36	1151.98

Analyses of variances applied to log transformed values for all data	df	P > F	P > F	P > F	P > F
Soil P	1	<0.0001	<0.0001	<0.0001	<0.0001
Residue	1	0.0125	0.7494	0.0390	0.2882
Freezing	1	0.1874	0.3796	0.6901	0.2016
Soil P X Freezing	1	0.0329	0.1565	0.1801	0.0281
Soil P X Residue	1	0.3327	0.0916	0.3374	0.3899
Freezing X Residue	1	0.2710	0.808	0.8562	0.3859
Soil P X Freezing X Residue	1	0.0644	0.7013	0.3449	0.2358

Table B.2. Soluble reactive P (SRP) concentration in simulated runoff from soil, residue and freezing treatments (arithmetic means).

Group means	Treatment	First Duration (0-15 minute)	Second Duration (15-30 minute)	Third Duration (30-60 minute)	Overall duration (0-60 minute)
		$\mu g\ L^{-1}$			
Soil P	+	240.2	64.81	54.81	119.58
	-	19.2	5.31	4.12	9.46
Residue	+	229.2	30.12	21.56	92.95
	-	30.2	40.	37.37	36.09
Freezing	+	39.7	29.93	30.68	33.48
	-	219.7	40.18	28.25	95.56
Soil P X Freezing	- -	10.62	4.62	3.50	6.15
	- +	27.87	6.0	4.75	12.76
	+ -	428.87	75.75	53.0	184.96
	+ +	51.62	53.87	56.62	54.21
Soil P X Residue	- -	3.12	4.5	5.12	4.34
	- +	35.37	6.12	3.12	14.58
	+ -	57.37	75.5	69.62	67.84
	+ +	423.12	54.12	40.0	171.32
Freezing X Residue	- -	34.12	48.25	42.75	42.01
	- +	405.37	32.12	13.75	149.10
	+ -	26.37	31.75	32.0	30.17
	+ +	53.12	28.12	29.37	36.80
Soil P X Freezing X Residue	- - -	3.50	3.75	3.75	3.67
	- - +	17.75	5.50	3.25	8.64
	- + -	2.75	5.25	6.50	5.01
	- + +	53.0	6.75	3.0	20.52
	+ - -	64.75	92.75	81.75	80.35
	+ - +	793.0	58.75	24.25	289.566
	+ + -	50.0	58.25	57.50	55.33
	+ + +	53.25	49.50	55.75	53.08

Analyses of variances applied to log transformed values for all data	df	P > F	P > F	P > F	P > F
Soil P	1	<0.0001	<0.0001	<0.0001	<0.0001
Residue	1	0.0142	0.8358	0.0679	0.2457
Freezing	1	0.2071	0.4031	0.7906	0.2308
Soil P X Freezing	1	0.0356	0.1648	0.2146	0.0322
Soil P X Residue	1	0.337	0.0962	0.3367	0.3930
Freezing X Residue	1	0.2843	0.7685	0.7672	0.3634
Soil P X Freezing X Residue	1	0.0611	0.608	0.5168	0.1832

Table B.3. Soluble reactive P (SRP) export loads from soil, residue and freezing treatments subjected to simulated runoff (arithmetic means).

Group means	Treatment	Runoff loss (0-60 minute)	Percolate loss (0-60 minute)	Total loss (runoff + percolate)
			g ha^{-1}	
Soil P	+	93.11	231.17	324.29
	-	7.75	37.98	45.74
Residue	+	70.94	152.01	222.96
	-	29.92	117.14	147.07
Freezing	+	25.80	101.96	127.76
	-	75.06	167.20	242.2
Soil P X Freezing	- -	5.15	18.87	24.031
	- +	10.35	57.09	67.45
	+ -	144.97	315.52	460.50
	+ +	41.24	146.82	188.07
Soil P X Residue	- -	3.715	18.908	22.62
	- +	11.79	57.06	68.86
	+ -	56.137	215.38	271.52
	+ +	130.08	246.97	377.06
Freezing X Residue	- -	36.626	173.61	210.23
	- +	113.508	160.79	274.30
	+ -	23.226	60.68	83.90
	+ +	28.37	143.24	171.61
Soil P X Freezing X Residue	- - -	3.052	36.14	39.19
	- - +	7.263	1.60	8.870
	- + -	4.379	1.67	6.05
	- + +	16.32	112.52	128.85
	+ - -	70.20	311.08	381.277
	+ - +	219.75	319.977	539.73
	+ + -	42.07	119.68	161.76
	+ + +	40.42	173.96	214.38
Analyses of variances applied to log transformed values for all data		P > F	P > F	P > F
Soil P	1	<0.0001	<0.0001	<0.0001
Residue	1	0.2882	0.3558	0.0227
Freezing	1	0.2016	0.2513	0.1167
Soil P X Freezing	1	0.0281	0.0043	0.0008
Soil P X Residue	1	0.3899	0.6249	0.2520
Freezing X Residue	1	0.3859	<0.0001	<0.0001
Soil P X Freezing X Residue	1	0.2358	<0.0001	<0.0001

Table B.4. Volume of runoff collected in simulated runoff experiment (geometric means).

Means Factors	Treatment			Runoff water (L) First Duration (0-15 minute)	Second Duration (15-30 minute)	Third Duration (30-60 minute)	Overall duration (0-60 minute)
Soil P		+		7.05671	7.209159	8.366654	22.65477
		-		7.480188	7.470578	8.600486	23.56265
Residue		+		7.334821	7.207061	8.093733	22.64027
		-		7.196566	7.472753	8.890495	23.57774
Freezing		+		7.179802	7.214391	8.284098	22.77144
		-		7.351946	7.465161	8.686195	23.44193
Soil P X Freezing	-		-	7.526241	7.494658	8.648	23.67286
	-		+	7.434417	7.446575	8.553233	23.45296
	+		-	7.181688	7.43578	8.724559	23.21325
	+		+	6.933907	6.989446	8.023432	22.10973
Soil P X Residue	-		-	7.413614	7.595621	9.019579	24.03666
	-		+	7.54736	7.347593	8.200866	23.09799
	+		-	6.985872	7.351873	8.763258	23.12759
	+		+	7.128267	7.069216	7.988	22.19162
Freezing X Residue	-		-	7.240968	7.583963	9.292584	24.13365
	-		+	7.464626	7.34822	8.119376	22.77003
	+		-	7.152436	7.363175	8.505804	23.03464
	+		+	7.207273	7.068613	8.068171	22.51125
Soil P X Freezing X Residue	-	-	-	7.357805	7.521348	8.774886	23.65497
	-	-	+	7.698533	7.468062	8.522949	23.69077
	-	+	-	7.469846	7.670627	9.271095	24.42451
	-	+	+	7.399156	7.229068	7.890954	22.50246
	+	-	-	7.125986	7.647098	8.249368	24.62203
	+	-	+	7.237826	7.230301	7.734913	21.88507
	+	+	-	6.847935	7.068046	7.803684	21.72385
	+	+	+	7.020366	6.911719	9.840825	22.52005

Analyses of variances applied to log transformed values for all data	df	P > F	P > F	P > F	P > F
Soil P	1	0.0005	0.0292	0.2600	0.0326
Residue	1	0.1998	0.0269	0.0006	0.0278
Freezing	1	0.1137	0.0357	0.0588	0.1068
Soil P X Freezing	1	0.4367	0.0835	0.1409	0.2669
Soil P X Residue	1	0.9372	0.8466	0.9582	0.9663
Freezing X Residue	1	0.4377	0.7659	0.0985	0.3200
Soil P X Freezing X Residue	1	0.2787	0.1749	0.0002	0.0023

Table B.5. Soluble reactive P (SRP) export loads from soil, residue and freezing treatments subjected to simulated runoff (geometric means).

Group means	Treatment			First Duration (0-15 minute)	Second Duration (15-30 minute)	Third Duration (30-60 minute)	Overall duration (0-60 minute)
				g P ha^{-1}			
Soil P		+		900.92	11.25829	9.424844	49.46816
		-		2.341654	1.11678	0.981489	4.505853
Residue		+		178.9944	3.36486	2.070793	18.27207
		-		11.78619	3.736568	4.467072	12.19874
Freezing		+		23.18021	3.06635	2.832761	11.69494
		-		91.01128	4.100324	3.2655	19.0592
Soil P X Freezing	-		-	1.483276	1.018663	0.826297	3.724392
	-		+	3.696779	1.224347	1.165829	5.451282
	+		-	5584.299	16.50463	12.90515	97.5335
	+		+	145.3488	7.679607	6.883118	25.08983
Soil P X Residue	-		-	0.365078	0.884833	1.213288	3.128297
	-		+	15.01758	1.409527	0.793976	6.490022
	+		-	380.5052	15.77917	16.44683	47.5688
	+		+	2133.14	8.03268	5.400902	51.44336
Freezing X Residue	-		-	13.23997	4.152528	4.643538	13.21368
	-		+	625.6097	4.04881	2.296415	27.49067
	+		-	10.49203	3.362275	4.297311	11.26176
	+		+	51.21242	2.79647	1.867339	12.14479
Soil P X Freezing X Residue	-	-	-	0.348161	0.826113	0.834604	2.750808
	-	-	+	6.319215	1.256092	0.818073	5.042555
	-	+	-	0.382817	0.947728	1.763791	3.557588
	-	+	+	35.69899	1.581705	0.770588	8.352984
	+	-	-	503.4931	20.87303	25.83555	63.4728
	+	-	+	61936.09	13.05046	6.446272	149.8718
	+	+	-	287.5595	11.92842	10.47	35.64977
	+	+	+	73.46745	4.944188	4.525056	17.65788

Analyses of variances applied to log transformed values for all data	df	P > F	P > F	P > F	P > F
Soil P	1	<0.0001	<0.0001	<0.0001	<0.0001
Residue	1	0.0125	0.7494	0.0390	0.2882
Freezing	1	0.1874	0.3796	0.6901	0.2016
Soil P X Freezing	1	0.0329	0.1565	0.1801	0.0281
Soil P X Residue	1	0.3327	0.0916	0.3374	0.3899
Freezing X Residue	1	0.2710	0.808	0.8562	0.3859
Soil P X Freezing X Residue	1	0.0644	0.7013	0.3449	0.2358

Table B.6. Soluble reactive P (SRP) export from soil, residue and freezing treatments subjected to simulated runoff (geometric means).

Group means	Treatment			First Duration (0-15 minute)	Second Duration (15-30 minute)	Third Duration (30-60 minute)	Overall duration (0-60 minute)
				µg			
Soil P		+		547.0549	320.8544	268.5725	1409.839
		-		41. 24497	31.83118	27.96968	128.4163
Residue		+		271.1676	95.89826	59.00831	520.754
		-		83.20783	106.5001	127.3022	347.6621
Freezing		+		111.623	87.40017	80.72537	333.305
		-		202.1381	116.8553	93.05486	543.1854
Soil P X Freezing	-		-	33.82173	29.0312	23.54775	106.1436
	-		+	50.29747	34.90122	33.22199	155.3607
	+		-	1208.093	470.362	367.7297	2779.693
	+		+	247.7202	218.8688	196.1527	715.0601
Soil P X Residue	-		-	18.40281	25.22245	34.57643	89.15576
	-		+	92.43958	40.17153	22.62533	184.9656
	+		-	376.2221	449.6897	468.6965	1355.705
	+		+	795.4586	228.9302	153.8974	1466.136
Freezing X Residue	-		-	87.5053	118.3398	132.3413	376.5876
	-		+	466.941	115.3895	65.43088	783.4841
	+		-	79.1214	95.845	122.455	320.9583
	+		+	157.4757	79.6994	53.21616	346.1266
Soil P X Freezing X Residue	-	-	-	18.02287	23.54309	23.78701	78.39769
	-	-	+	63.4699	35.79863	23.3109	143.7128
	-	+	-	18.79075	27.0216	50.25977	101.3901
	-	+	+	134.632	45.07858	21.95992	238.06
	+	-	-	424.859	594.837	736.2933	1808.959
	+	-	+	3435.233	371.9344	183.6566	4271.346
	+	+	-	333.153	339.9601	298.3544	1016.018
	+	+	+	184.1955	140.9094	128.9604	503.2519

Analyses of variances applied to log transformed values for all data	df	P > F	P > F	P > F	P > F
Soil P	1	<0.0001	<0.0001	<0.0001	<0.0001
Residue	1	0.0125	0.7494	0.0390	0.2882
Freezing	1	0.1874	0.3796	0.6901	0.2016
Soil P X Freezing	1	0.0329	0.1565	0.1801	0.0281
Soil P X Residue	1	0.3327	0.0916	0.3374	0.3899
Freezing X Residue	1	0.2710	0.808	0.8562	0.3859
Soil P X Freezing X Residue	1	0.0644	0.7013	0.3449	0.2358

Appendix C

EFFECT OF P STATUS IN SOIL ON WATER EXTRACTABLE NUTRIENTS FROM CROP RESIDUES

C.1 Introduction

The magnitude and forms of phosphorus losses from agricultural land are always controlled by many factors include soil test phosphorus (STP), landscape slope, rainfall intensity and many other management practices such as tillage and residues cover. One of these factors, soil test P, could affect the P losses directly or indirectly. The direct effect is simply defined by the positive linear relationship between the soil P concentration and the P losses through surface runoff. For example, Tarkalson and Milkkelsen (2004) reported that the potential for dissolved and particulate P loss through soil erosion, surface runoff, and subsurface drainage increase as soil P increases. Similarly, Sawka et al. (2007) and Wright et al. (2006) have observed similar relation in Manitoba and Alberta, respectively. In addition, soil test P concentration may affect P losses indirectly by influencing the P concentration in crop tissues which are considered to be an important source of the P losses from agriculture lands especially in a cold climate. Phosphorus concentration in plant tissues could be influenced by STP by increasing the concentration of water soluble P extractable from plant tissue. Therefore, the total P loss from field is a result of the interaction between vegetative and soil sources of P. Roberson et al. (2007) found a weak relationship between soil test P and fresh alfalfa TP content ($r=0.39$), and no correlation between soil test P and SRP or TDP in fresh alfalfa ($r=0.01$

to 0.02). However, they observed significant relationships between soil test P and water extractable P from alfalfa tissue that was frozen and thawed, or dried.

C.2 Objective of the Study

The main objectives of this study were:1) to measure the water extractable P in the residue samples under frozen and unfrozen conditions; 2) to examine the influence of soil test P concentrations on the potential amount of P that might leach from crop residues during snowmelt and rainfall runoff events.

C.3 Material and Methods

C.3.1 The Area of Study

This study was conducted using crop residues from a field experiment on a Newdale clay loam soil near Brandon, MB, Canada that was established in 1999 to evaluate liquid swine manure and composted cattle manure as crop fertilizers and as amendments (Buckley 2005). Characteristics of the soil at this site after the three years of fertility treatment applications are presented in Table C.1. Soil and crop residue samples for the current experiment were collected from four of the five original treatments, including a control (CK) "no fertilizer or manure applied", swine manure (SM), composted beef manure (C), and composted manure with 20 kg N ha^{-1} (urea) added (CU). The experimental design was a RCB, with four replicates of each treatment and a plot size of 4m x 35m. From 1999 to 2002, manure was applied to the plots on the basis of N requirements of the barley, flax and wheat crops that were grown. However, no manure was applied to the plots after 2002. In 2003, oats (cv. Assiniboia) were seeded along with perennial alfalfa; the alfalfa was killed in midsummer 2006 and winter wheat (cv. Raptor) was planted. The winter wheat grain was harvested in August 2007 and straw was also removed by baling.

Soil and crop residues were collected on September 15, 2007. Ten cores of soil samples were collected randomly from the top 0-20 cm of each plot. Soil samples were air dried and ground to less than 2 mm size prior to analyses. Soil P was analyzed using the Olsen method (sodium bicarbonate extraction). Crop residues were collected from the middle of each plot as 0.5 m by 0.5 m quadrats. Two subsamples of each residue sample were weighed into separate polyethylene bags for the water extraction; each subsample represented one quarter of the original sample. A small additional sample of residue was used for determining the moisture content by drying for 48 h at 65°C. The moisture content was used for calculation the vegetative residue and nutrient extracted on a dry matter basis, in addition to the area basis.

C.3.2 Residue Sampling and Extraction

For extraction, 1.5 L of deionized water was added to each bag on an area basis equivalent to 1.5 cm of runoff or a snow depth of approximately 15 cm. The bags were secured by cable ties, then rolled and mixed to ensure all vegetation was in contact with water. The first set of samples was soaked for 24 hrs at room temperature and then frozen for 24 hrs. Samples were then thawed for 36 hrs and gently mixed by rolling the bag. However, the second set of the samples was not exposed to freezing and thawing treatment after the 24 hrs soaking step, so that the potential of nutrients leaching from unfrozen residues could be measured. After incubation, bags were emptied into household plastic colanders that were placed in plastic pails; the colanders had openings of approximately 5 mm and were used to separate most of the residues from the extracts. Samples were allowed to drain in the colanders for 1 min before removing the colanders and allowing the extracts to settle for another 5 min. A 500 mL subsample of extract was then gently decanted into a storage bottle for analyses.

C.3.3 Analyses of Extracts

Soluble reactive phosphorus was analysed by using the ascorbic acid-molybdate blue method (Murphy and Riley 1962).

Table C.1. Soil chemical properties after the three years of fertility treatment applications

Plot treatment [z]	Soil depth (cm)					
	0-10	10-20	0-10	10-20	0-10	10-20
	Soil pH		E.C. (ms/ cm)		Olsen extractable P (ppm)	
CK	8.03 ± 0.08	8.14± 0.15	2.42 ± 0.28	2.44 ± 0.47	10.0 ± 0.9	3.1 ± 0.5
SM	7.91± 0.15	8.16± 0.17	3.00 ± 0.37	2.55 ± 0.26	35.5 ± 10.2	6.3 ± 1.4
CU	7.92± 0.11	8.00± 0.16	3.81 ± 0.36	2.61 ± 0.48	86.2 ± 9.9	10.5 ± 1.9
C	8.00± 0.12	8.11± 0.17	4.94 ± 1.08	3.73 ± 1.33	128.1 ± 15	10.4 ± 1.8

[z] Plot treatments: CK = Unfertilized, SM = Liquid Swine Manure; CU = Compost / Urea, C = Compost Only. E.C. = Electrical Conductivity.

C.3.4 Statistical Analyses

Microsoft Excel was used to determine correlation between extractable (SRP and TDP) from residues and soil test P.

C.4 Results and Discussion

The concentrations of SRP and TDP extracted from residue by both exposing or without exposing of residue to freezing and thawing treatments were significantly correlated to the soil test P where the crops has grown. However, this correlation was greater in the frozen-thawed residues than in the unfrozen residues (Figures C.1 and C.2 respectively). Similar trends were found for the correlations between soil test P and SRP/ TDP yield per kg biomass (Figures C.3 and C.4 respectively) and also between soil test P and yield of extractable SRP and TDP in crop residues expressed on the area basis (Figures C.5 and C.6).

These results indicate that high P uptake by plants in response to high soil test P could in turn increase the potential for P loss to runoff. Complementary results were found in other studies. For example, Blair et al. (1987) compared the amount of phosphorus (^{32}P) uptake by white clover from soil with high and low P concentration. They also compared the amount of P released from residue of the crops grown in these soils. They found uptake was greatest from the high P soils which also associated with a higher plant yield, dry matter and higher plant phosphorus content. Simultaneously, the net release of phosphorus from the plant material was significantly higher from residue in the high soil P compared to the other in the low soil P.

The effect of freezing and thawing on increasing of the extractable P from residue was illustrated by the comparison of the correlations between soil test P and the extractable vegetative P for frozen-thawed versus unfrozen treatments. Average concentrations and yields of SRP and TDP were 40-50 % greater for residues that were frozen and thawed than for unfrozen residues. These correlations indicate that the potential risk of P loss from crop material is higher in the cold climate than in warm climates due to freezing and thawing causing increased rupturing of tissues and greater release of vegetative P (Bechmann et al. 2005). In another study, Roberson et al. (2007) also found the soluble reactive phosphorus (SRP) extracted from alfalfa crops increased significantly by exposing these residues to freezing or drying treatments than from untreated fresh alfalfa.

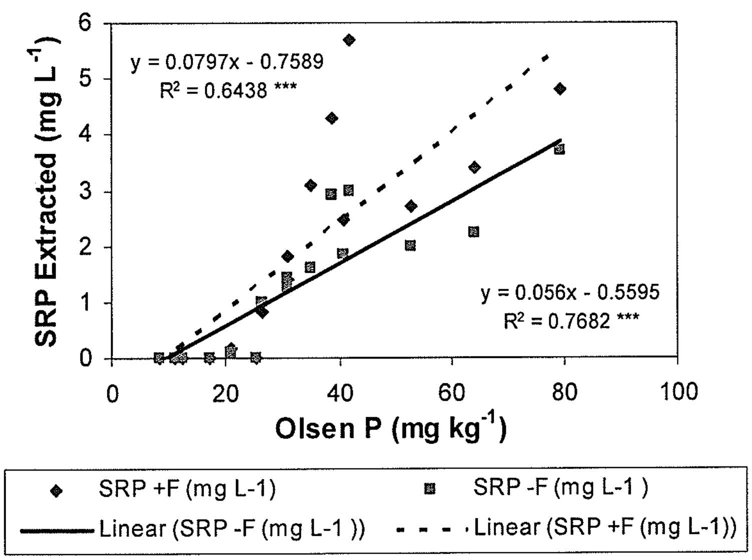


Figure C.1. The correlations between soil test P (mg kg^{-1}) and SRP (mg L^{-1}) extracted from residue by exposing (+F) or without exposing (-F) to freezing & thawing treatment. *** = Significant at ($P < 0.001$).

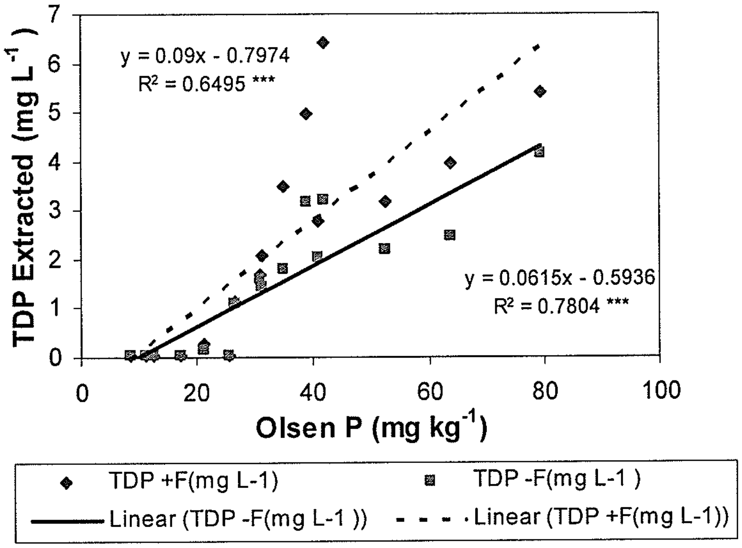


Figure C.2. The correlations between soil test P (mg kg^{-1}) and TDP (mg L^{-1}) extracted from residue by exposing (+F) or without exposing (-F) to freezing & thawing treatment. *** = Significant at (P < 0.001).

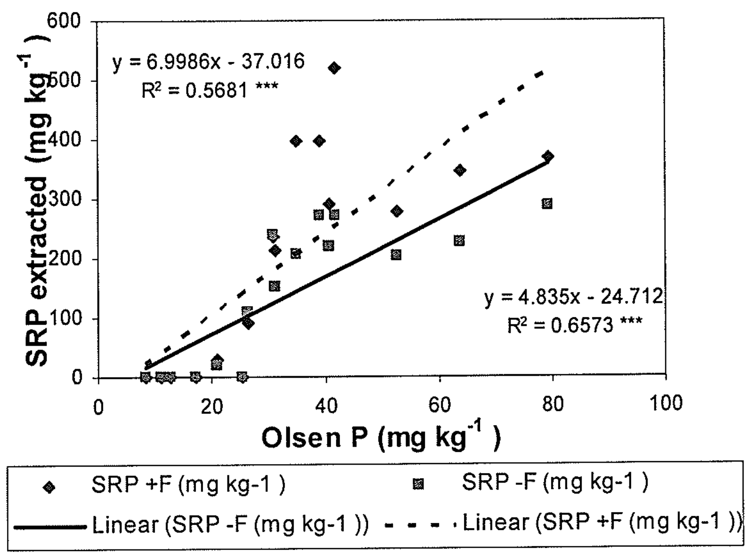


Figure C.3. The correlations between soil test P (mg kg^{-1}) and SRP (mg kg^{-1}) extracted from residue by exposing (+F) or without exposing (-F) to freezing & thawing treatment. *** = Significant at (P < 0.001).

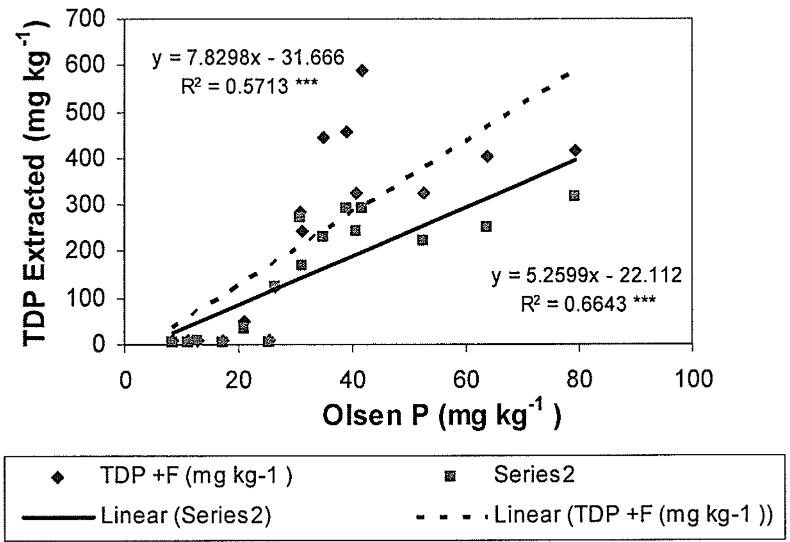


Figure C.4. The correlations between soil test P (mg kg $^{-1}$) and TDP (mg kg $^{-1}$) extracted from residue by exposing (+F) or without exposing (-F) to freezing & thawing treatment *** = Significant at (P < 0.001).

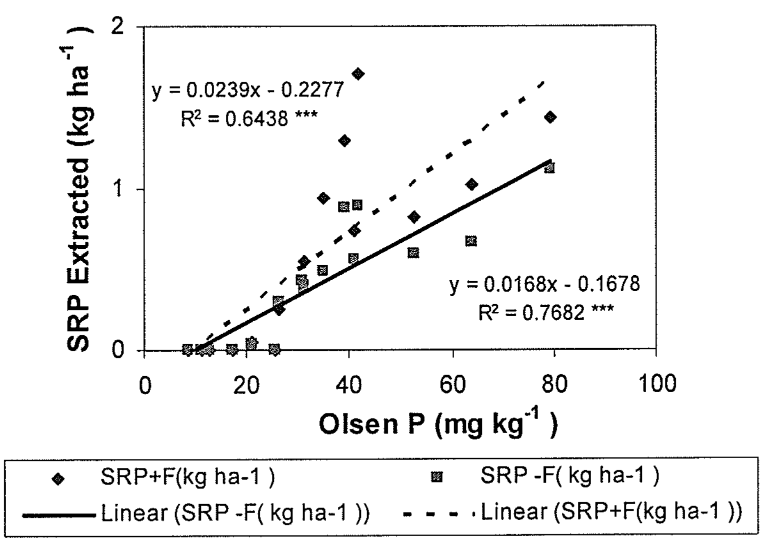


Figure C.5. The correlations between soil test P (mg kg $^{-1}$) and SRP (mg ha $^{-1}$) extracted from residue by exposing (+F) or without exposing (-F) to freezing & thawing treatment. *** = Significant at (P < 0.001).

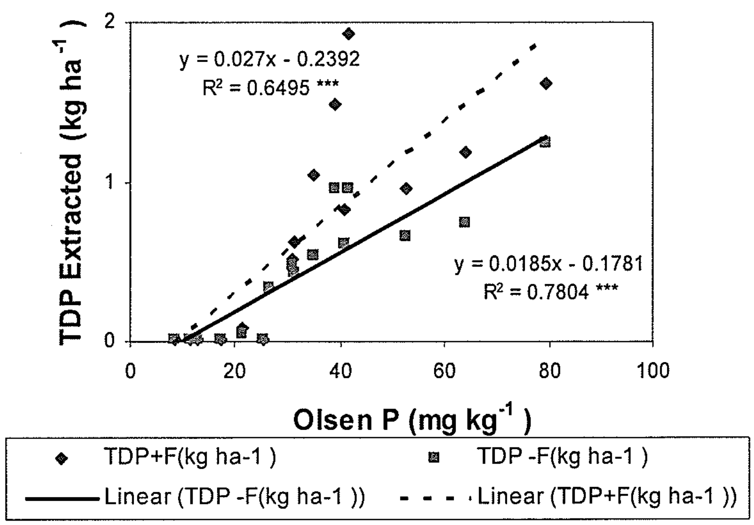


Figure C.5. The correlations between soil test P (mg kg^{-1}) and TDP (mg ha^{-1}) extracted from residue by exposing (+F) or without exposing (-F) to freezing & thawing treatment. *** = Significant at ($P < 0.001$).

C.5 Summary and Conclusions

In addition to the direct impact of soil test P on P loss from soil to runoff, our results indicate that the potential risk of P loss is compounded by the effect of soil test P on concentration of water extractable P in the residues of crops grown on these soils. This indirect effect was observed in unfrozen and frozen-thawed residues. Average concentration and yields of SRP and TDP were 40-50 % greater for residues that were frozen and thawed than for unfrozen residues. Therefore, the positive relationship between soil test P and the extractable P from residue likely occurs in both warm and cold climates. However, in the cold climate, the risk of the P loss from residue is greater than in the warm climate due to the effect of freezing-thawing on the rupturing of plant cells leading to more P release from residue to runoff.

C.6 References

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Table C. 2. The extracted SRP and TDP from residue (mg /L) with and without exposing to wetting, freezing and thawing treatment.

SRP +F (mg L^{-1})	SRP –F (mg L^{-1})	TDP +F (mg L^{-1})	TDP –F (mg L^{-1})	Biomass (T ha^{-1})	Olsen P (mg kg^{-1})
4.3	2.9	5.0	3.2	3.25	38.9
3.1	1.6	3.5	1.8	2.35	34.9
5.7	3.0	6.4	3.2	3.28	41.7
1.4	1.4	1.7	1.6	1.79	30.8
0.2	0.1	0.3	0.2	1.62	21.2
0.8	1.0	1.1	1.1	2.72	26.5
0.0	0.0	0.0	0.0	1.35	11.3
0.0	0.0	0.0	0.0	1.84	12.8
1.8	1.3	2.1	1.4	2.55	31.1
0.0	0.0	0.1	0.0	2.58	25.5
0.0	0.0	0.1	0.0	2.01	17.2
0.0	0.0	0.0	0.0	1.87	8.6
3.4	2.2	4.0	2.5	2.94	63.9
4.8	3.7	5.4	4.2	3.91	79.3
2.5	1.9	2.8	2.1	2.55	40.8
2.7	2.0	3.2	2.2	2.94	52.7

Table C. 3. The extracted SRP and TDP from residue (mg /kg) with and without exposing to wetting, freezing and thawing treatment.

SRP +F (mg kg^{-1})	SRP –F (mg kg^{-1})	TDP +F (mg kg^{-1})	TDP –F (mg kg^{-1})	Biomass (T ha^{-1})	Olsen P (mg kg^{-1})
397	270	459	294.1	3.25	38.9
397	206	446	229.7	2.35	34.9
520	271	588	292.8	3.28	41.7
235	240	284	269.9	1.79	30.8
31	21	50	32.2	1.62	21.2
92	110	125	122.8	2.72	26.5
0	0	9	5.8	1.35	11.3
0	0	7	6.7	1.84	12.8
214	150	242	168.3	2.55	31.1
0	0	6	3.6	2.58	25.5
0	0	7	4.5	2.01	17.2
0	0	8	4.7	1.87	8.6
345	226	404	253.0	2.94	63.9
367	286	415	318.8	3.91	79.3
290	218	325	241.7	2.55	40.8
278	202	325	222.3	2.94	52.7

Table C. 4. The extracted SRP and TDP from residue (kg/ ha) with and without exposing to wetting, freezing and thawing treatment.

SRP+F (kg ha $^{-1}$)	SRP –F (kg ha $^{-1}$)	TDP+F (kg ha $^{-1}$)	TDP –F (kg ha $^{-1}$)	Biomass (T ha $^{-1}$)	Olsen P (mg kg $^{-1}$)
1.3	0.9	1.5	1.0	3.25	38.9
0.9	0.5	1.0	0.5	2.35	34.9
1.7	0.9	1.9	1.0	3.28	41.7
0.4	0.4	0.5	0.5	1.79	30.8
0.0	0.0	0.1	0.1	1.62	21.2
0.2	0.3	0.3	0.3	2.72	26.5
0.0	0.0	0.0	0.0	1.35	11.3
0.0	0.0	0.0	0.0	1.84	12.8
0.5	0.4	0.6	0.4	2.55	31.1
0.0	0.0	0.0	0.0	2.58	25.5
0.0	0.0	0.0	0.0	2.01	17.2
0.0	0.0	0.0	0.0	1.87	8.6
1.0	0.7	1.2	0.7	2.94	63.9
1.4	1.1	1.6	1.2	3.91	79.3
0.7	0.6	0.8	0.6	2.55	40.8
0.8	0.6	1.0	0.7	2.94	52.7